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Vol. 1

Canadian Seismic Agreement

Technical Report Covering
1979 - 1985

Prepared by P. W. Basham, J. A. Lyons, J. A. Drysdale, W. E. Shannon,
F. Andersen, R. B. Hayman, R. J. Wetmiller

Canadian Commercial Corporation

Prepared for
U.S. Nuclear Regulatory Commission

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1. INTRODUCTION

1.1 Background

The United States Nuclear Regulatory Commission (USNRC) has a need to understand the distribution and causes of earthquakes in the eastern United States, which have not been studied as adequately as in the more seismic regions of the western part of the country. In order to determine better these seismic characteristics, a USNRC research program has been developed which endeavours to delineate active features and to determine the levels of seismic activity associated with them. This requires detailed monitoring by strategically situated networks of closely spaced seismographs. Several networks have been installed, including the North Eastern United States Seismic Network (NEUSSN) which monitors the entire northeastern U.S.

The seismically-active features of the northeastern U.S. are only part of a much larger zone of activity extending from Lake Erie to the Canadian Maritime provinces and offshore to the edge of the continental shelf, and northward into eastern Ontario, western Quebec and the lower St. Lawrence valley. Monitoring of Canadian seismicity is the responsibility of the Earth Physics Branch (EPB) of the Canadian Department of Energy, Mines and Resources.

In 1978, informal discussion between USNRC and EPB took place to find a mechanism whereby USNRC could obtain regular access to seismological data, information and research reports on the more seismically-active areas in eastern Canada adjacent to the U.S. This led, in 1979, to the Canadian Seismic Agreement, a contract between the USNRC and the Canadian Commercial Corporation, with contract performance under the direction of EPB.

1.2 Canadian Seismic Agreement 1979-1984

The first Canadian Seismic Agreement contract (NRC-04-79-180) was in effect from 01 April 1979 to 31 March 1984, and was extended to 31 May 1984. Under this agreement the USNRC received the following items and services:

i) access to the data generated by the Eastern Canadian Telemetered Network (ECTN);

ii) preliminary epicenters and phase information on earthquakes in the vicinity of the U.S.-Canada border; and

iii) analysed data, such as focal mechanisms, isoseismals and final hypocenters, and data from other seismic stations in Canada.

In early 1979, the ECTN consisted of ten stations with data recording on-line at the Seismological Laboratory in Ottawa. The funds obtained by EPB under this agreement were expended for capital expansion of the ECTN, non-recurring R & D costs, data telemetry line rentals, and hardware and software developments in the Seismological Laboratory.

The major portion of this report constitutes the final report of achievements under this agreement, including descriptions of the current ECTN and its data acquisition and processing systems in the Seismological Laboratory, and a summary of eastern Canadian earthquakes and associated research results whose data capture and study were, in part, made possible by the expanded ECTN.

1.3 Canadian Seismic Agreement 1984-1986

In 1983, in further informal discussions between USNRC and EPB, USNRC expressed an interest in continuing the original Canadian Seismic Agreement and expanding the agreement to include gaining access to data from an expanded network of strong motion seismographs in eastern Canada. Administrative arrangements for the new agreement took most of 1984, and the new contract (NRC-04-85-110) with the Canadian Commercial Corporation was signed in February, 1985. This agreement is in effect from 01 June 1984 to 31 March 1986, and it is anticipated that the contract will be renewed annually for a minimum of five years.

Under this agreement the USNRC will receive the same items and services described under Section 1.2 above, and, in addition will receive preliminary copies of the film from the strong motion seismograph network in eastern Canada for all significant recorded strong motion, and will have access to digitized, corrected and analysed data.

The additional funds obtained by EPB under this agreement will be expended for capital acquisition and installation of an expanded strong motion seismograph network centred on the Charlevoix seismic zone in the lower St. Lawrence valley, and on the maintenance and operation of this network. During 1984, EPB commenced this strong motion network expansion and the final section of this report constitutes an interim report on this work. This interim report replaces the four quarterly reports for 30 June, 30 September and 31 December 1984, and 31 March 1985 specified in the new contract.

2. EASTERN CANADIAN TELEMETERED NETWORK

2.1 Introduction

The period 1979-1984 has seen the expansion of the ECTN from ten stations to twenty-two stations. This was one of the major goals of the first Canadian Seismic Agreement, and has had a significant impact on our ability to determine regional seismicity accurately. During the five year period, quarterly and annual reports have described the evolution of hardware and software which has been developed and used to achieve the current configuration. Further details, including calibration information, are published annually by the Earth Physics Branch in its bulletin "Canadian Seismograph Operations".

ECTN is located in Eastern Canada with headquarters in Ottawa. Figure 1 shows the current network layout, with special symbols indicating the stations that have been added since 1979. Information on the stations is given in Table 1. An independent western network currently comprising 18 stations is located in south-western British Columbia with headquarters at Sydney, BC. Although the details are different, essentially the same specifications, hardware & software apply to both networks.

The networks were first established in the early 1970's with the aim of providing high quality digitized waveform data in real-time from regional seismic events. Design goals were to record broadband short period data with wide signal dynamic range; to have conventional seismograms created at the central site; to develop software tools and hardware to permit time series to be displayed on a computer terminal; and to have a means of rapidly determining earthquake epicentres. It was hoped that the availability of high

Figure 1. Eastern Canadian telemetered network.

Table 1. Eastern Canada Telemetered Network Stations

STATION	LAT. (°N)	LONG. (°W)	ELEVATION (m)	OPERATING DATES
Ottawa, Ont. (OTT)	45.3942	75.7167	77	Feb. 24/74 to Apr. 25/78; Jan. 26/79 to date
Montréal, Qué. (MNT)	45.5025	73.6230	112	Feb. 24/74 to date
Manicouagan, Qué. (MNQ)	50.5333	68.7744	564	Nov. 27/74 to date
Gentilly, Qué. (GNT)	46.3628	72.3722	10	Apr. 26/78 to date
Glen Almond, Qué (GAC)	45.7033	75.4783	62	Oct. 26/79 to date
La Pocatière, Qué. (LPQ)	47.3408	70.0094	126	June 6/80 to date
Sherbrooke, Qué. (SBQ)	45.3783	71.9264	265	Aug. 12/80 to date
Val-d'Or, Qué. (VDQ)	48.2300	77.9717	305	Dec. 9/80 to date
Williamsburg, Ont. (WBO)	45.0003	75.2750	85	Dec. 9/80 to date
Chalk River, Ont. (CKO)	45.9944	77.4500	190	Jan. 12/81 to date
Mont-Tremblant, Qué. (TRQ)	46.2222	74.5556	853	Mar. 16/81 to date
Grand-Remous, Qué. (GRQ)	46.6067	75.8600	290	Mar. 16/81 to date
Grosses-Roches, Qué. (GSQ)	48.9142	67.1106	398	Oct. 28/81 to date
Edmundston, N.B. (EBN)	47.462	68.242	195	Oct. 28/81 to date
St. George, N.B. (GGN)	45.117	66.822	30	Oct. 28/81 to date
Caledonia Mtn., N.B. (LMN)	45.852	64.806	363	Oct. 28/81 to date
McKendrick L., N.B. (KLN)	46.8433	66.3717	411	Jan. 28/82 to date
Hauterive, Qué. (HTQ)	49.1917	68.3939	123	Apr. 15/82 to date
Welcome, Ont. (WEO)	44.0186	78.3744	149	Apr. 30/82 to date
La Grande-4, Qué (KAQ)	53.9833	73.5230	472	Mar. 21/83 to date
Sudbury, Ont. (SUO)	46.4027	81.0068	252	Mar. 8/84 to date
Eldee, Ont. (EEO)	46.6411	79.0733	398	Dec. 16/84 to date

quality machine-readable data would lead to novel waveform processing techniques and hence to an improved understanding of the earthquake processes. Although it has taken longer than expected, most of these goals have now been achieved. This Section gives an overview of the ECTN system and the factors that influenced its design. It then describes in more detail the hardware and software that has been developed, and finally comments on the overall system performance.

2.2 System Overview

The ECTN currently consists of twenty-two telemetered seismograph stations, a radio and telecommunications network, and a central data acquisition and data analysis facility located at Ottawa. In addition, events from an autonomous local processor installed at Sudbury are gathered daily using a dial-up telephone link.

A typical outstation consists of a short period seismometer located in a surface vault and an electronics package which digitizes the seismograph signal at 60 samples per second (s/s). Both telephone lines and UHF radio links are used to telemeter the digital data to the Data Laboratory at Ottawa. Radio links are used for the nearby stations, and for stations located in extremely remote areas to gain access to the national telephone network. Block diagrams of the telephone and radio networks are shown in Figures 2 and 3, respectively. A unidirectional asynchronous protocol is employed on the data transmission links with aggregate data rates between 1200 bits/sec and 9600 bits/sec on any one link. These systems receive the multichannel digital seismic data, order them, and write them into a five minute data buffer. Earthquakes and other seismic events are identified and saved as event files for later processing. Conventional monitor records are obtained from approximately half of the channels.

The raw event data are transferred directly to a VAX 11/750 for editing, analysis and archiving. High resolution graphics terminals permit seismologists to display data and pick phases for epicentral determination. Data are archived onto 6250 bpi tape organized as a series of event files. Copies of these tapes are available to external users.

Two of the stations in the network are unique. GAC includes a borehole seismometer from which 3 SP and 3 LP components are recorded, whilst at Sudbury, the SP data are processed by an autonomous local event processor modelled after the central-site ECTN system.

2.3 System Design Considerations

Conventional photographic and hot stylus seismographs have a dynamic range of about 40 dB with the result that many interesting events are clipped and only first arrivals can be read. Conventional long period seismograms can be manually digitized but this is out of the question for short period seismograms because of the high frequency content of the signals.

The digitizing parameters of ECTN were chosen to maximize system bandwidth, sampling rate and dynamic range, but this was constrained by the lack of suitable storage media and the high cost of data transmission. Figure 4 shows the portion of the ground motion spectrum that can be recorded by the ECTN system in comparison with conventional seismographs.

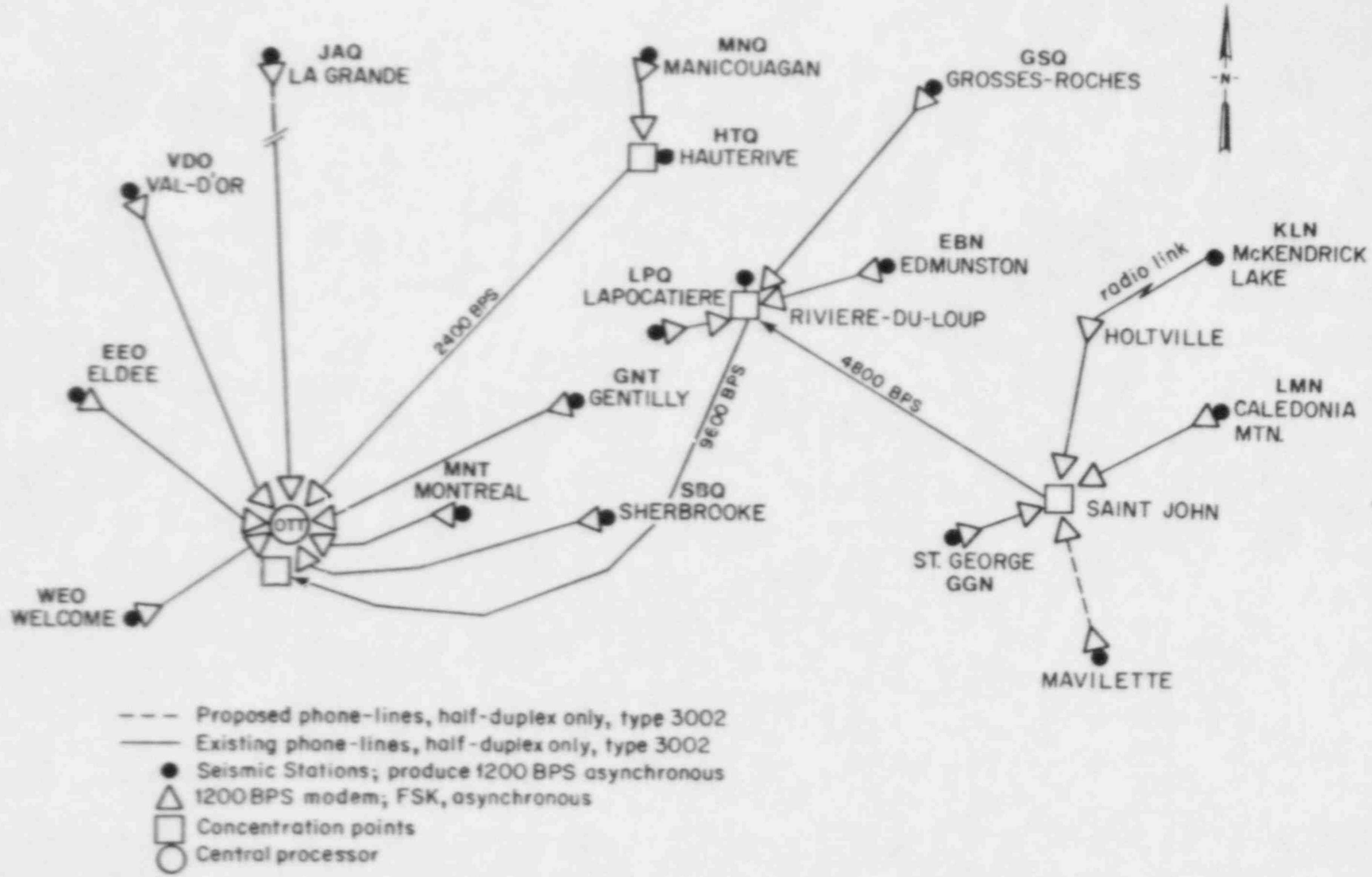


Figure 2. Block diagram: telephone telemetry network.

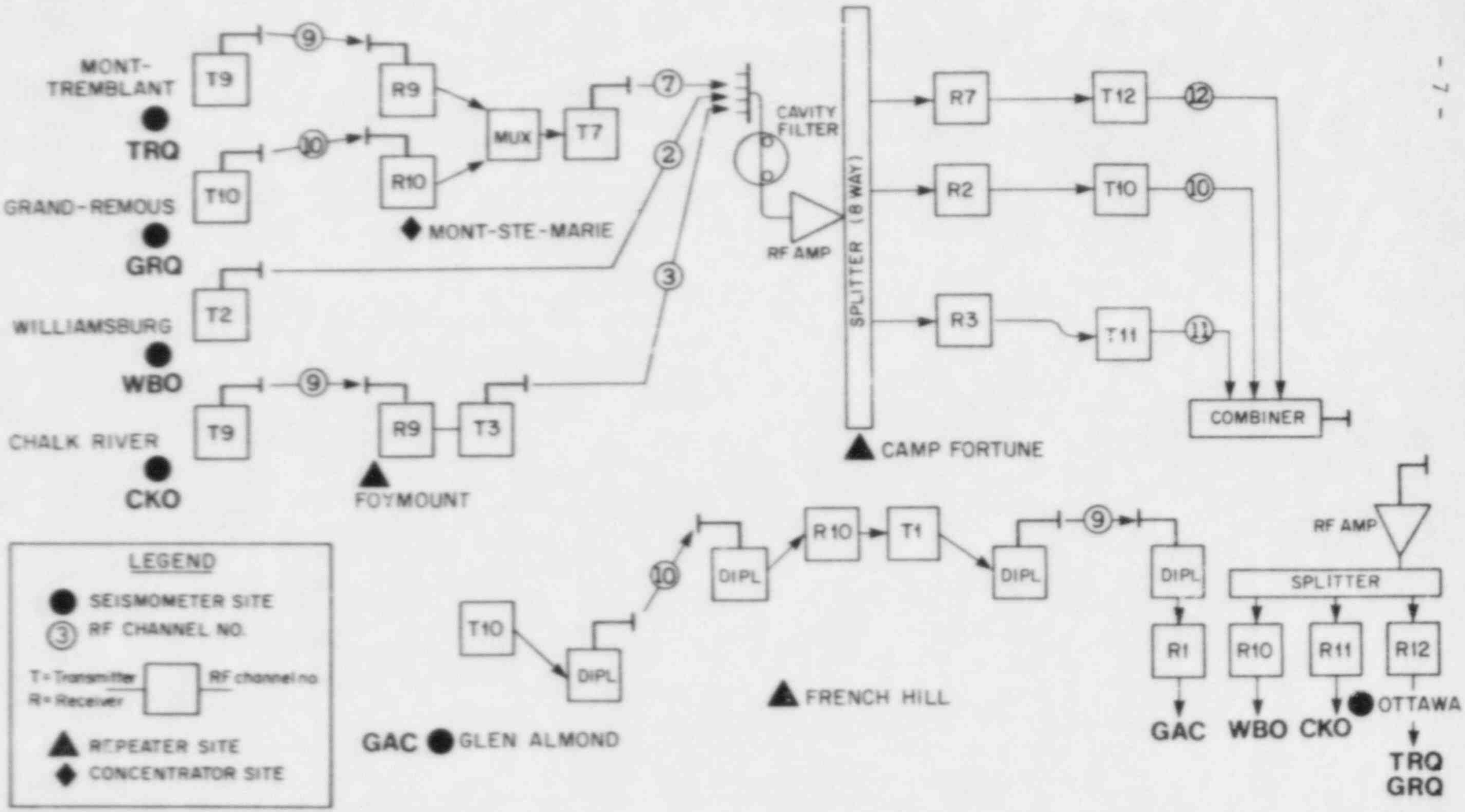


Figure 3. Block diagram: radio telemetry network.

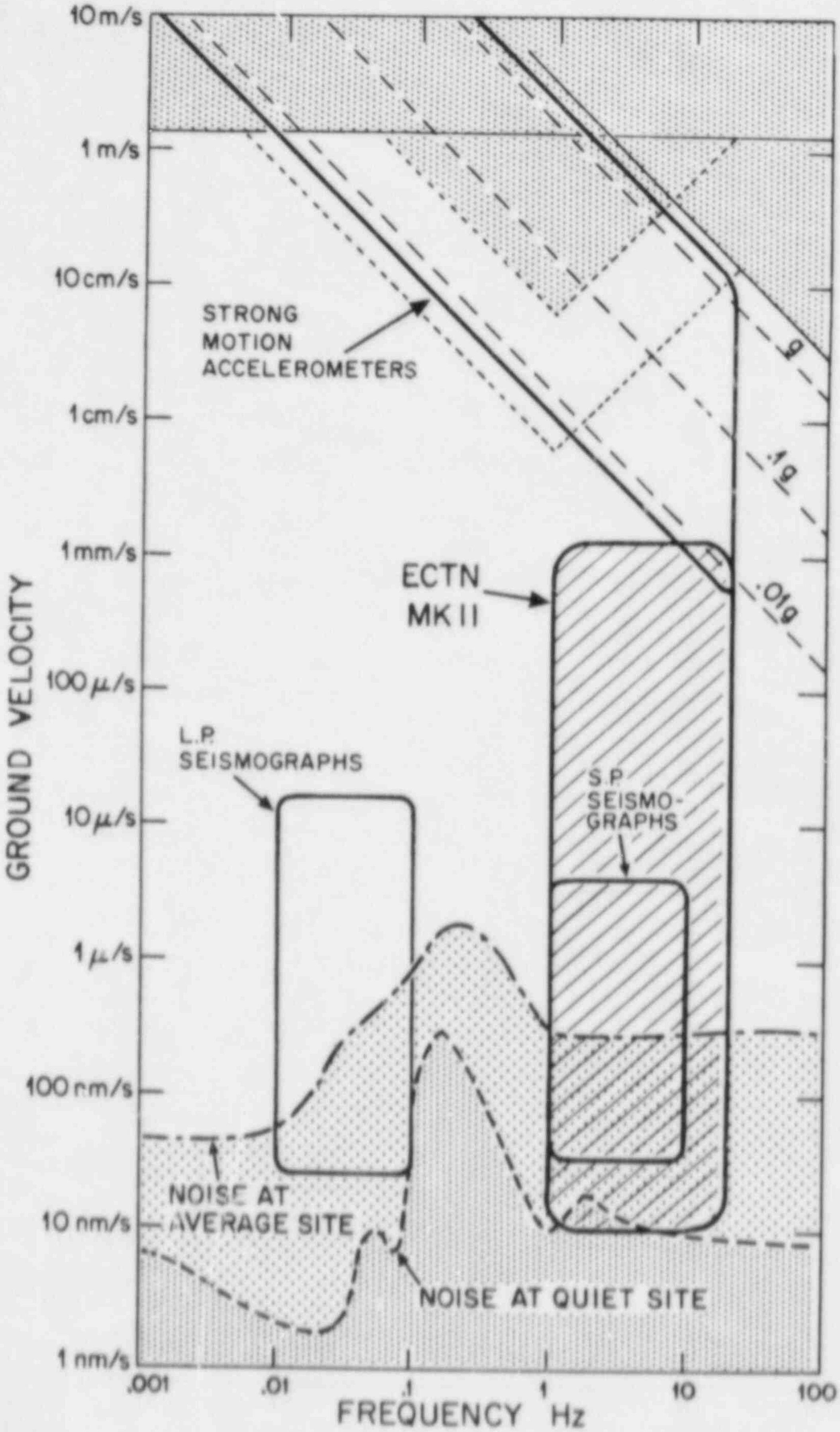

10 m/s
1 m/s
10 cm/s
1 cm/s
1 mm/s
100 μ/s
10 μ/s
1 μ/s
100 nm/s
10 nm/s
1 nm/s
GROUND VELOCITY
.001
.01
.1
1
10
100
FREQUENCY Hz
STRONG MOTION ACCELEROMETERS
g
.1g
.01g
ECTN MK II
L.P. SEISMOGRAPHS
S.P. SEISMO-GRAPHS
NOISE AT AVERAGE SITE
NOISE AT QUIET SITE

Figure 4

On the most sensitive gain, the ADC digitizes the background seismic noise with a resolution of 10 nm/sec/bit. This is quite satisfactory at most sites, but is perhaps marginal at very quiet sites on the Canadian Shield where the peak-to-peak background noise can be as low as 100 nm/sec. The corresponding clipping level at most sites is at a ground velocity of 2.6 mm/sec peak-to-peak.

The nominal system responses are shown in Figures 5, 6, 7 and 8. Mark I stations have 3 dB corner frequencies at 1 and 20 Hz with an anti-alias filter roll-off of 30 dB per octave. This yields - 18 dB rejection at the folding frequency and -50 dB at 60 Hz. Mark II stations have corners at 1 Hz and 16 Hz, with anti-alias filters rolling off at 18 dB per octave to give -16 dB at 30 Hz and -34 dB at 60 Hz. The actual S-plane transfer functions for the various configurations are given at the bottom of each figure.

The system design required the outstation hardware to have high reliability and to be capable of operating in an outdoor environment in sub-arctic winters and humid summers. These factors influenced our choice of a central timing system, and simple asynchronous data communications. Station power consumption is sufficiently low that outstations can operate for one year from a set of primary electrical cells.

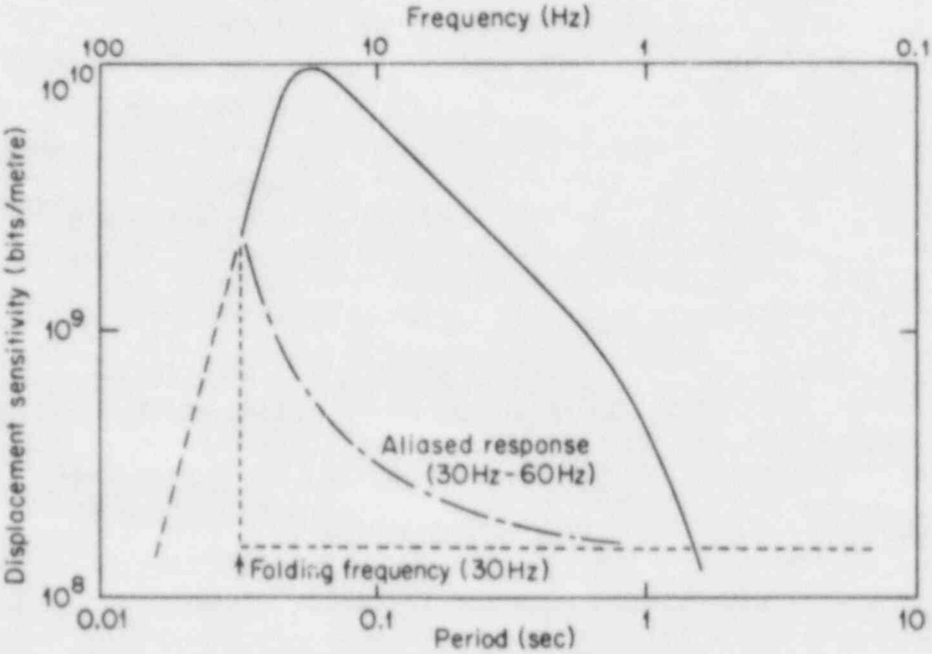
Clearly, 1970's technology could not accommodate continuous recording of digital data, and an event detector was a practical necessity. A design goal was to permit distant earthquakes from Arctic Canada to be properly recorded. These are typified by a 2 to 3 minute emergent P-phase followed by a relatively strong S-phase. It was recognized that many events would not trigger on the first arrival but rather on the stronger S-phase arrival. For distant local events S-P times of several minutes would need to be accommodated. Accordingly, received data was stored in a temporary ring buffer of five minutes duration to allow up to five minutes of pre-trigger data to be saved with the data. In practice, we have found that one minute of pre-trigger data is a more practical value in order to make the most effective use of the limited event storage space. The event detector was based on work done by D.H. Weichert for the Yellowknife Seismic Array but it was optimized to record regional as opposed to teleseismic events.

The station at Glen Almond was installed in 1979 with the aim of obtaining hands-on experience with the borehole seismometer that has been widely used in Seismic Research Observatories by the USGS.

The station at Sudbury was developed as an autonomous event triggered station since it was recognized that communications costs would preclude the use of continuous data telemetry from all seismograph sites in Canada. This system forms part of an exhibit in the science museum, "Science North", which was opened to the public in 1984. This station is viewed as a conceptual prototype of the kind of equipment that will eventually be used when the Canadian Seismograph Network is updated. The concepts which are expected to be utilized are

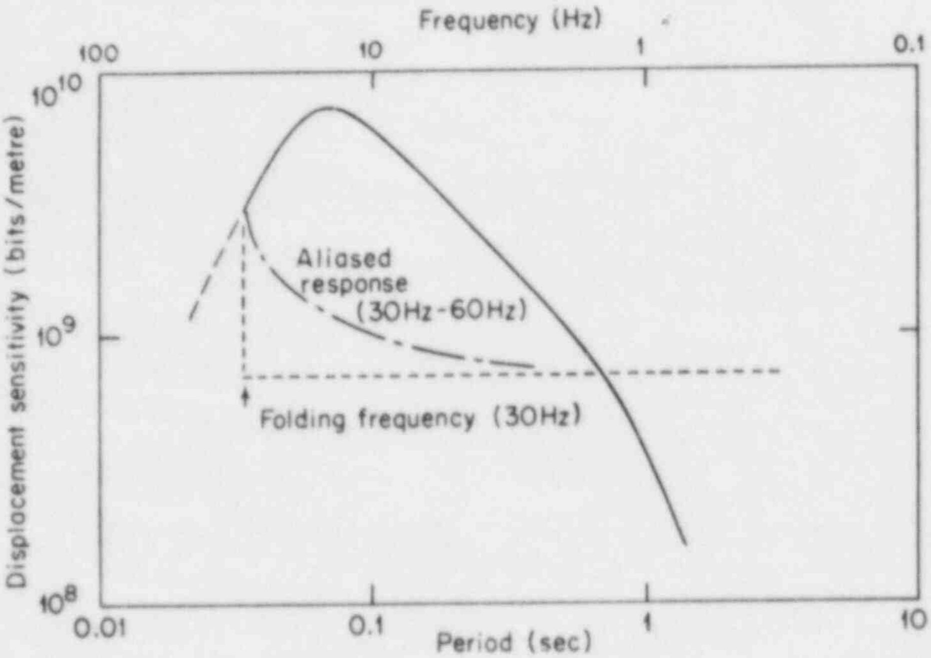
a) dial-up access to the data by high speed (9600 baud) telphone link,

b) that a station will consist of two parts, a fairly simple sensor and digitizing package with a full duplex serial link to a station processor,



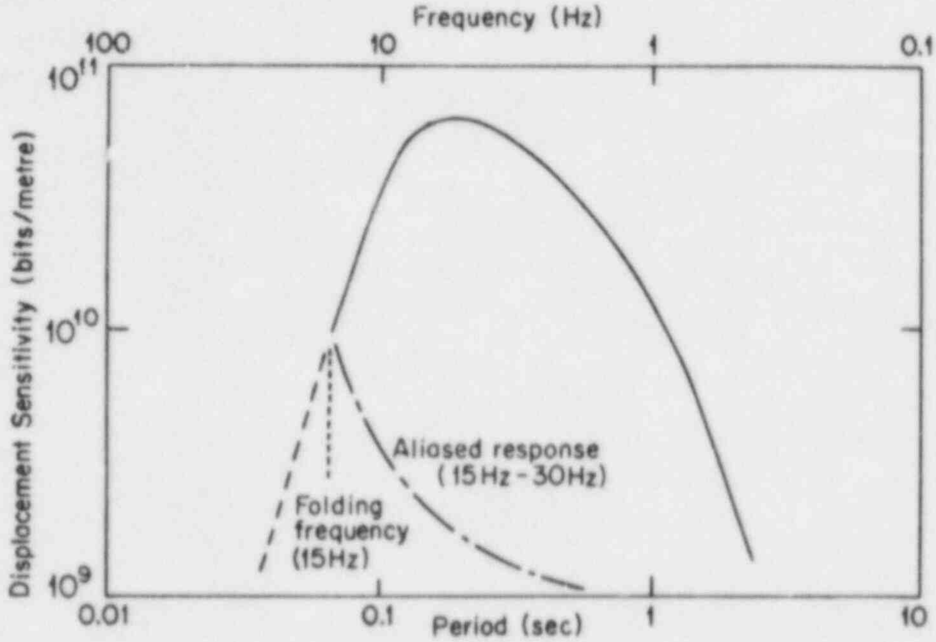

```
C
C     Transfer function for ECTN Mark I station.
C
               W=2*PI*FREQ
               S=CMPLX (0.0,W)
C
C     10 second high-pass single-pole filter - Wo=0.6283
C
               Z(1)=S/(S+0.6283)
C
C     S13 seismometer - Wo=6.283, D=0.707
C
               Z(2)=S**2/(S**2+8.8844*S+6.283**2)
C
C     20Hz low-pass five-pole filter-Wo=125.664, D=0.707
C
               Z(3)=125.664/(S+125.664)
               Z(4)=125.664**2/(S**2+203.324*S+125.664**2)
               Z(5)=125.664**2/(S**2+77.66*S+125.664**2)
C
C     Scale factor in bits per metre
               Z(6)=1.E08
C
               VELRESP=Z(1)*Z(2)*Z(3)*Z(4)*Z(5)*Z(6)
               DSPRESP=VELRESP*S
```

Figure 5. Displacement response and s-plane transfer function for ECTN Mark I stations.



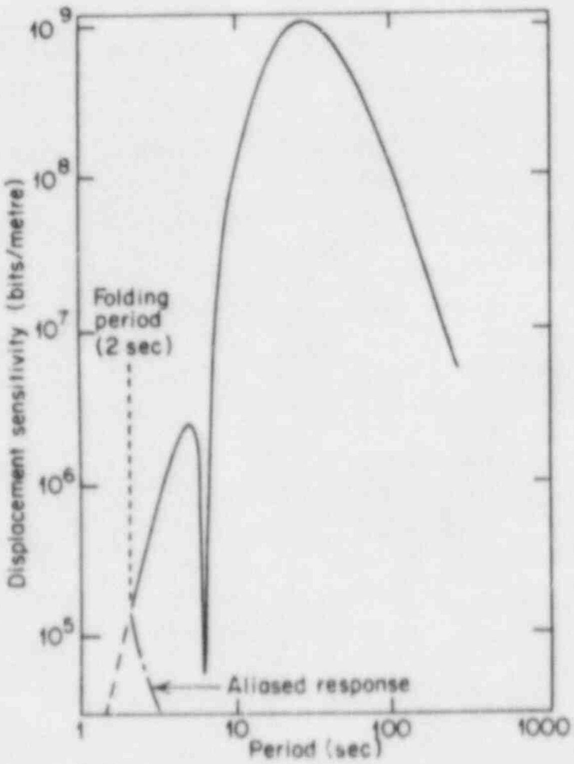

```
C
C     Transfer function for ECTN Mark II station.
C
          W=2*PI*FREQ
          S=CMPLX(0.0,W)
C
C     2 second high-pass single-pole filter - Wo= 3.1416
C
          Z(1)=S/(S+3.1416)
C
C     S13 seismometer - Wo= 6.283, D=0.707
C
          Z(2)=S**2/(S**2+8.8844 * S+6.283**2)
C
C     16Hz low-pass three-pole filter - W =100.531, D=0.707
C
          Z(3)=100.531/(S+100.531)
          Z(4)=100.531** 2/(S**2+100.531*S+100.531** 2)
C
C     Scale factor in bits per metre
          Z(5)=1.E08
C
          VELRESP=Z(1)*Z(2)*Z(3)*Z(4)*Z(5)
          DSPRESP=VELRESP*S
```

Figure 6. Displacement Response and s-plane transfer function for ECTN Mark II stations.




```
C
C     Transfer function for GAC short period components.
C
            W=2*PI*FREQ
            S=CMPLX(0.0,W)
C
C     KS 36000 seismometer - W(0)=4.488  D=0.80
            Z(1)=S**2/(S**2+7.181*S+4.488**2)
C
C     Nominal 52 second high-pass single-pole filter - W(0)=0.1396
            Z(2)=S/(S+0.1396)
C
C     15.9 Hz low-pass single-pole filter - W(0)=100
            Z(3)=100./(S+100)
C
C     Nominal 2 second high-pass single-pole filter - W(0)=4.488
            Z(4)=S/(S+4.488)
C
C     Nominal 8Hz high-pass single-pole filter - W(0)=28.27
            Z(5)=S/(S+28.27)
C
C     8Hz low-pass three-pole filter - W(0)=50.3
            Z(6)=52.58/(S+52.58)
            Z(6)=Z(6)*((49.2**2)/(S**2+50.18*S+49.2**2))
C
C     Scale factor in bits per metre
            Z(7)=.9860E+11
C
            DSPRESP=Z(1)*Z(2)*Z(3)*Z(4)*Z(5)*Z(6)*Z(7)
```

Figure 7. Displacement response and s-plane transfer functionfor GAC short period.




```
C     Transfer function for GAC long period components
         W=2*PI*FREQ
         S=CMPLX (0.0,W)
C
C     KS 36000 seismometer - W(0)=4.488, D=0.80
         Z(1)=S**2/(S**2+7.181*S+4.488**2)
C     Nominal 52 second high-pass single-pole filter - W(0)=0.1396
         Z(2)=S/(S+0.1396)
C     15.9 Hz low-pass single-pole filter - W(0)=100
         Z(3)=100./(S+100.)
C     670 second high-pass single-pole filter - W(0)=0.00942
         Z(4)=S/(S+0.00942)
C     250 second high-pass single-pole filter - W(0)=0.0251
         Z(5)=S/(S+0.0251)
C     37.6 second low-pass two-pole filter - W(0)=0.167, D=0.80
         Z(6)=(0.167**2)/(S**2+0.267*S+0.167**2)
C     20 second low-pass two-pole filter - W(0)=0.315, D=0.64
         Z(7)=(0.315**2)/(S**2+0.402*S+0.315**2)
C     6 second notch filter
         Z(8)=(S**2+1.10)/((S+3.93)*(S+0.282))
C     8 second low-pass three-pole filter - W(0)=0.785
         Z(9)=0.794/(S+0.794)
         Z(9)=Z(9)*(0.742**2)/(S**2+0.785*S+0.742**2)
C     Scale factor in bits per metre
         Z(10)=.1630E+13
C
      DSPRESP=Z(1)*Z(2)*Z(3)*Z(4)*Z(5)*Z(6)*Z(7)*Z(8)*Z(9)*Z(10)
```

Figure 8. Displacement response and s-plane transfer function for GAC long period.

c) that time will be obtained from a satellite based transmitter,

d) that there will be remote control of the station from the data centre,

e) that a single drum recorder will monitor one component where an operator is available to change the paper.

2.4 Outstation Description

Block diagrams of Mark I and Mark II outstations are shown in Figures 9 and 10, respectively. Mark I stations were designed, built and installed in 1973 and incorporated binary gain ranging with a 9 bit mantissa yielding a total dynamic range of 96 dB. Mark II stations were first installed in 1977 and incorporated improved dynamic range (108 dB) and resolution by using a 12 bit ADC, a 2 bit exponent, and gains of 1, 4, 16 and 64.

Differential amplifiers are used in the front-end amplifier to give a common mode signal rejection better than 60 dB and seismometer damping is established by plug-in resistor modules. The Mark I design incorporates a fifth order Butterworth Nyquist filter with corner frequency at 20 Hz, whilst the Mark II design has a third order Butterworth filter with corner at 16 Hz. During conversion, both mantissa and exponent are completely redetermined on each sample.

The samples from different sensors and components are assembled into blocks of bytes called packets. A given station can generate several different types of packet, each of which is identified by a unique code which is encoded serially using the most significant bit of each byte in the packet. At simple stations having only a single component, the packet consists of two bytes which then have 14 bits available for encoding the data value. At the data laboratory, the processor synchronizes on these longitudinal codes, reconstitutes the original data values, and strips off the packet structure so that the end user is unaware of this process having taken place. Some examples of the packet structures in use are shown in Figure 11.

Actual data transmission is in an 8 bit asynchronous format. For example, when start bits and stop bits are taken into account, a two byte packet is encoded as 20 bits. The sample rates used were determined by dividing the available baud rates by this factor of 20. Hence 30, 60 & 120 s/s correspond to the maximum sample rates that can be obtained using asynchronous data transmission at 600, 1200 & 2400 baud, respectively.

The outstation equipment is usually mounted on the antenna tower in a standard electrical equipment enclosure. An insulated "heat shield" prevents direct solar radiation from striking the equipment case and an air space between the heat shield and the case helps to minimize the summer temperature rise in the case. In winter, no protection is required since the equipment is designed to operate reliably at -40°C. Figure 12 shows a photograph of a typical installation.

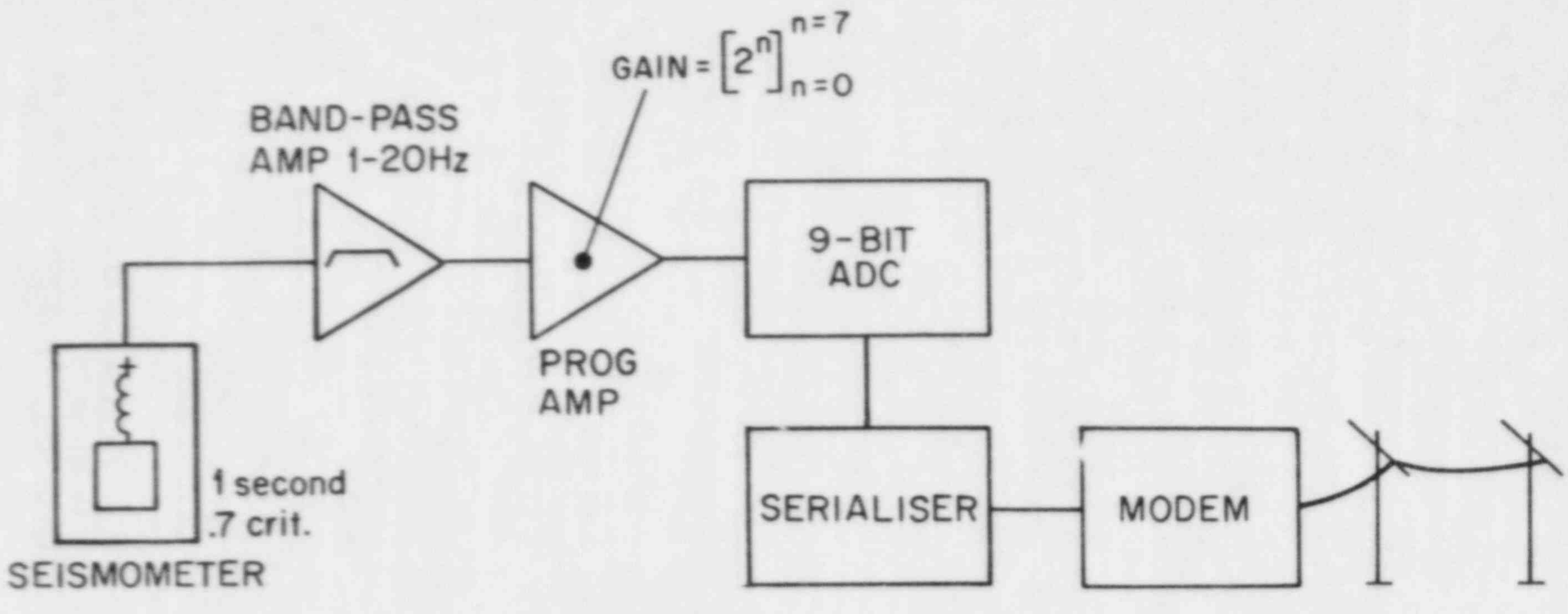


Figure 9. Block Diagram: ECTN Mark I Station.

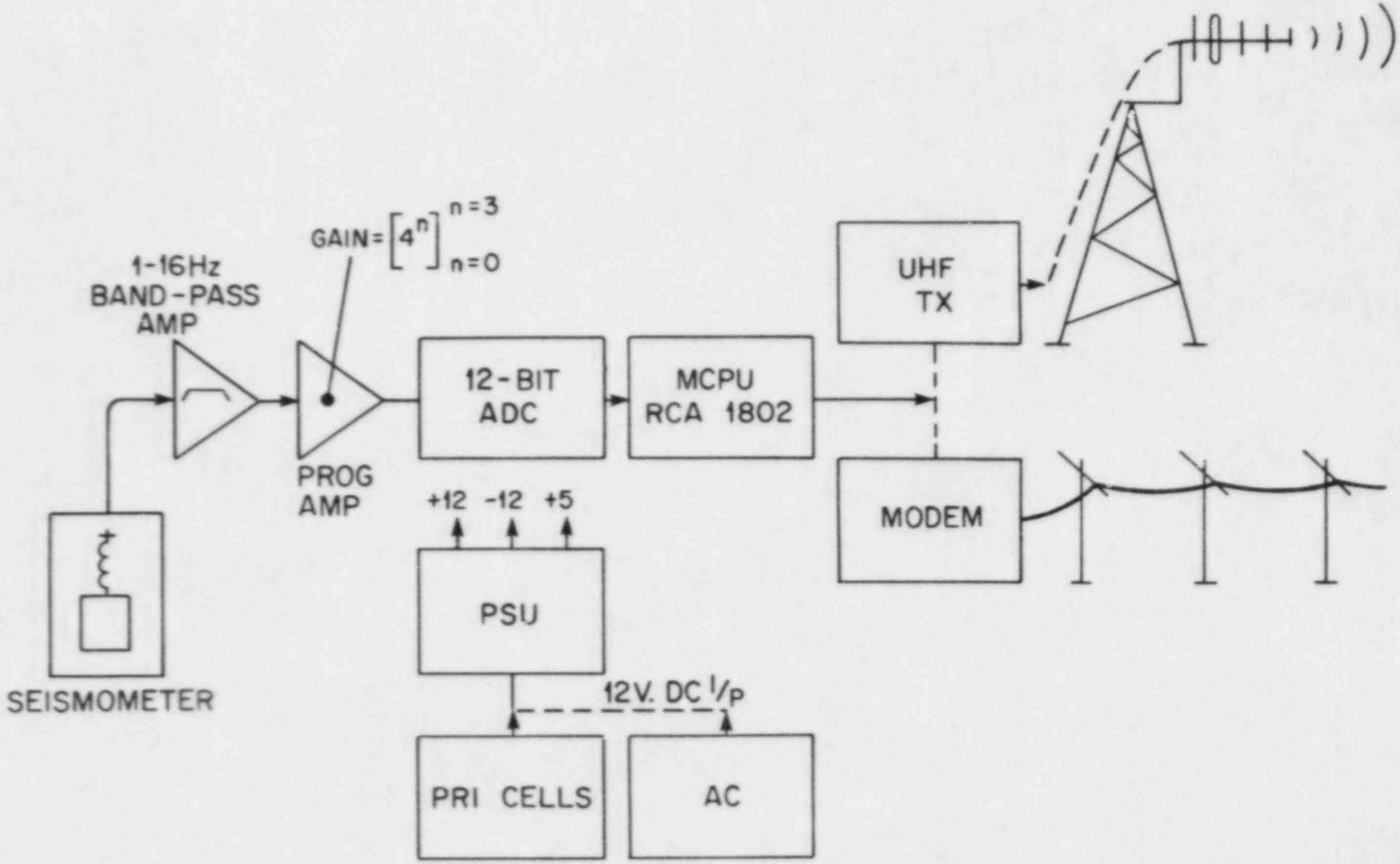


Figure 10. Block Diagram: ECTN Mark II Station.

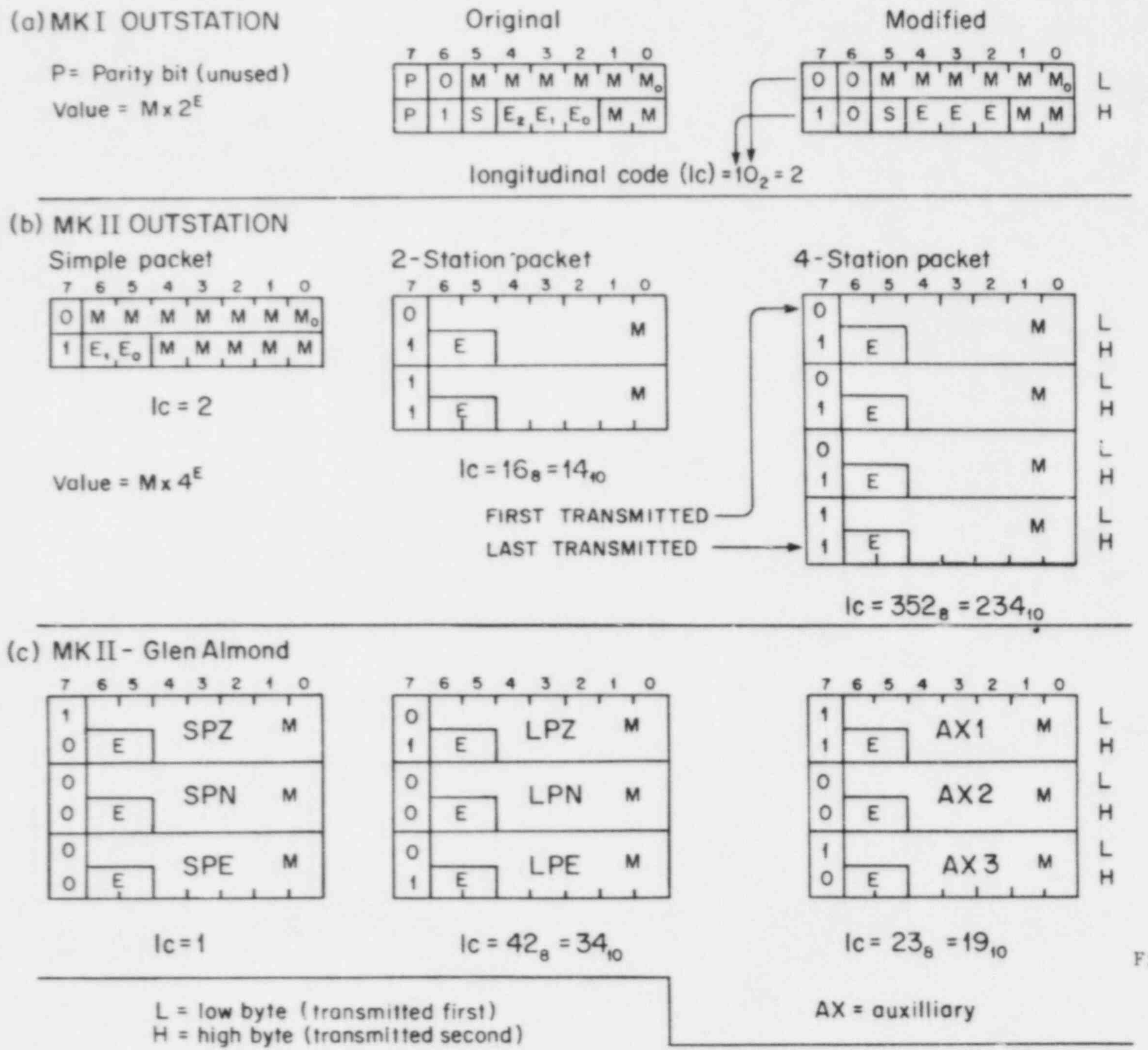

(a) MK I OUTSTATION
P = Parity bit (unused)
Value = M x 2^E
Original
Modified
longitudinal code (lc) = 10₂ = 2
(b) MK II OUTSTATION
Simple packet
lc = 2
Value = M x 4^E
2-Station packet
lc = 16₈ = 14₁₀
4-Station packet
FIRST TRANSMITTED
LAST TRANSMITTED
lc = 352₈ = 234₁₀
(c) MK II - Glen Almond
SPZ
SPN
SPE
LPZ
LPN
LPE
AX1
AX2
AX3
lc = 1
lc = 42₈ = 34₁₀
lc = 23₈ = 19₁₀
L = low byte (transmitted first)
H = high byte (transmitted second)
AX = auxilliary

Figure 11

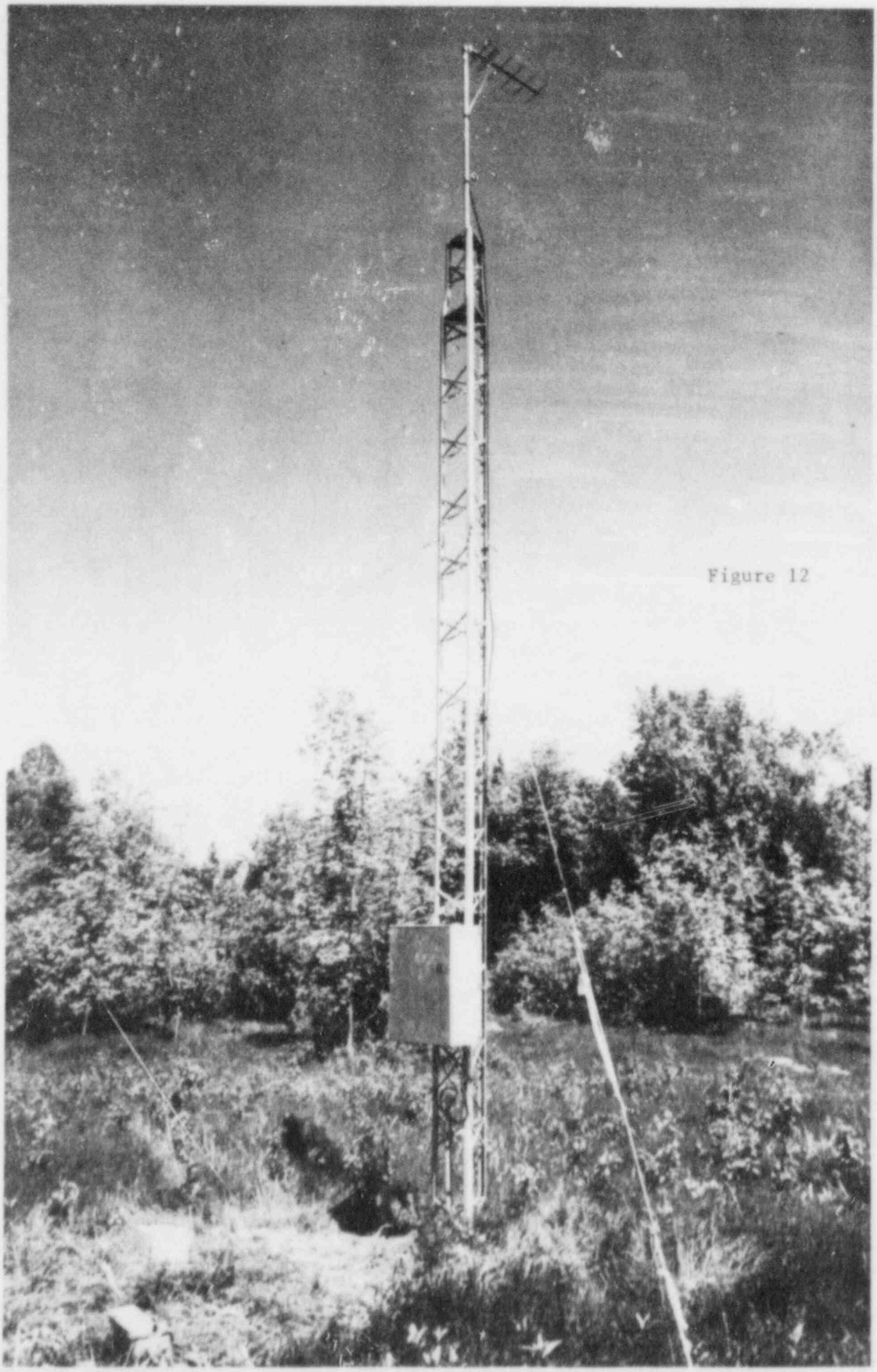


Figure 12

2.5 Multiplexing and Concentration

The multiplexing and concentration schemes both use the packet structure to encode multiple components or multiple stations onto a single bit stream enabling a more cost effective use of the communication system. By convention, multiplexing refers to combining components at a single station, whereas concentration is used to describe the process of combining data streams from two or more geographically separate stations.

The most complex example of multiplexing is the station at Glen Almond (GAC). As shown in Figure 11(c), three unique packet structures have been defined, one for three component short period data sampled at 30 s/s, one for three component long period data sampled at 1 s/s, and one for auxillary data sampled 1 per minute. The latter is present but has not been utilized so far. Room is made for the additional packets by omitting every thirtieth sample of the short period sensor. Subsequently a process in the data laboratory replaces this missing value with the value of the previous sample.

A concentrator receives data from two to four more distant stations and combines packets into larger packets for retransmission at a higher bit rate. Some earlier implementations combined the functions of digitizer and concentrator. While this was economical in hardware, it required too many different versions of the software, making software maintenance cumbersome. The current practice is to allow digitizing stations to include concentrators, but as functionally independent modules. It is permissible for the signal from a concentrator to be routed to a second concentrator for an additional degree of concentration. A set of tables within the concentrator firmware defines the exact configuration to be appropriate to the site needs. As an example, the block diagram of the concentrator at Rivière du Loup is shown in Figure 13.

2.6 Glen Almond

A block diagram of the station equipment at GAC is shown in Figure 14. A Geotech model 36000 tri-axial seismometer is installed at a depth of 100 metre . The downhole package is identical to that used in Seismic Research Observatories. The uphole electronics are different in that the short period amplifiers have been modified to provide a 1-10 Hz bandpass from the broadband signals. The three component signals from the LP and SP outputs are digitized by a standard ECTN gain ranging ADC at 1 s/s and 30 s/s respectively. The time multiplexed digital bit stream is transmitted by radio link at 1800 baud to the data laboratory where the vertical short period data stream is processed by the ECTN event detector and all six components are saved when a trigger occurs. In addition, continuous long period data are saved and archived as an independent dataset.

2.7 Sudbury

A block diagram of the station at Sudbury (SUO) is shown in Figure 15. A standard ECTN outstation is deployed at a rural location away from the cultural noise of the city. The data are telemetered to an event processor located in the city of Sudbury which triggers independently of the main ECTN processor at Ottawa and saves event files on a hard disc. The station is equipped with an independent timing system and drum recorder. The system can be completely controlled from the Data Laboratory at Ottawa, with the local operator only changing the seismograph paper. A dial-up 9600 baud telephone link is used to transfer the daily suite of event files to Ottawa for editing and merging with the main ECTN data set.

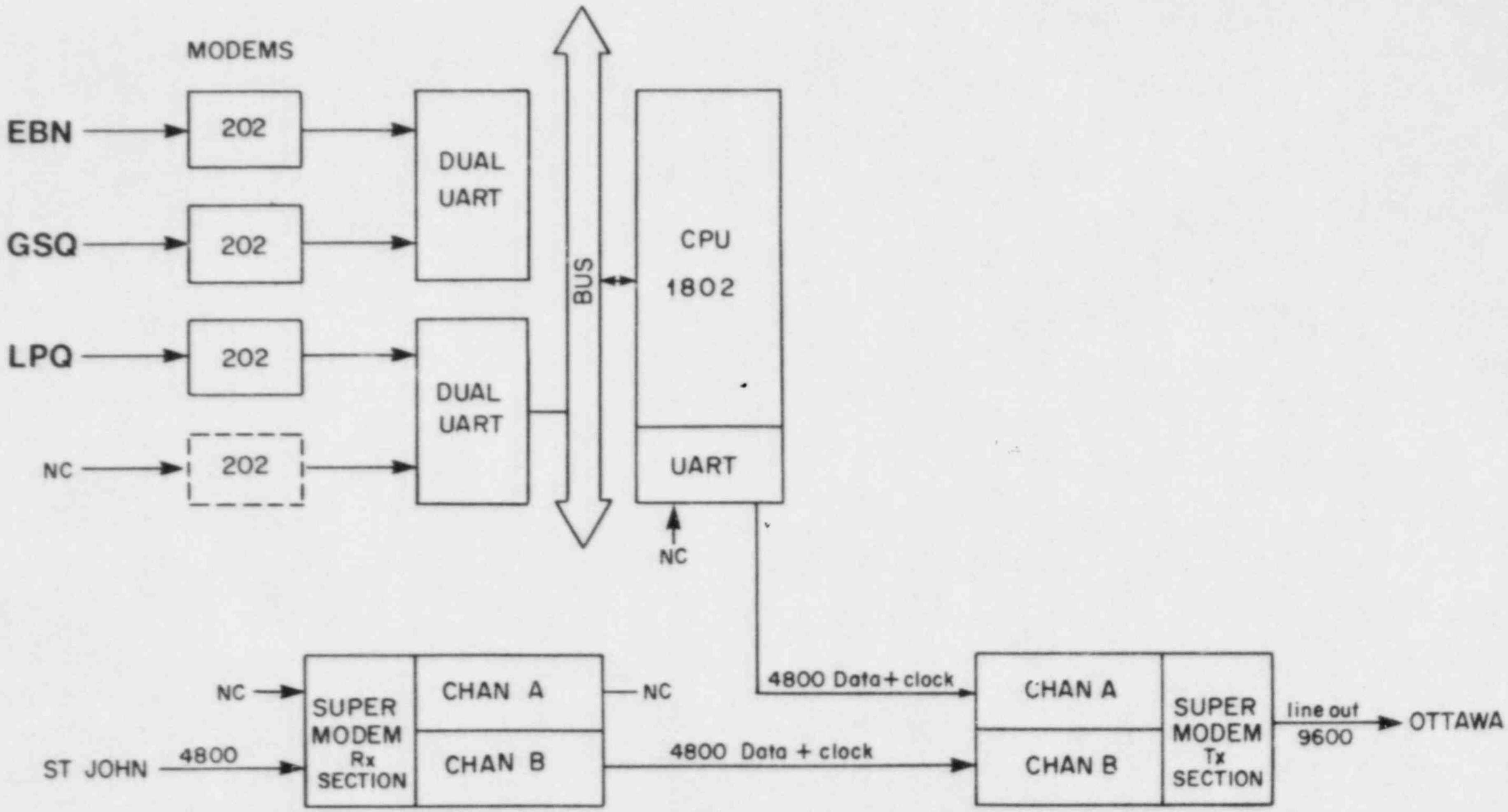


Figure 13. Block Diagram: Rivière du Loup concentrator.

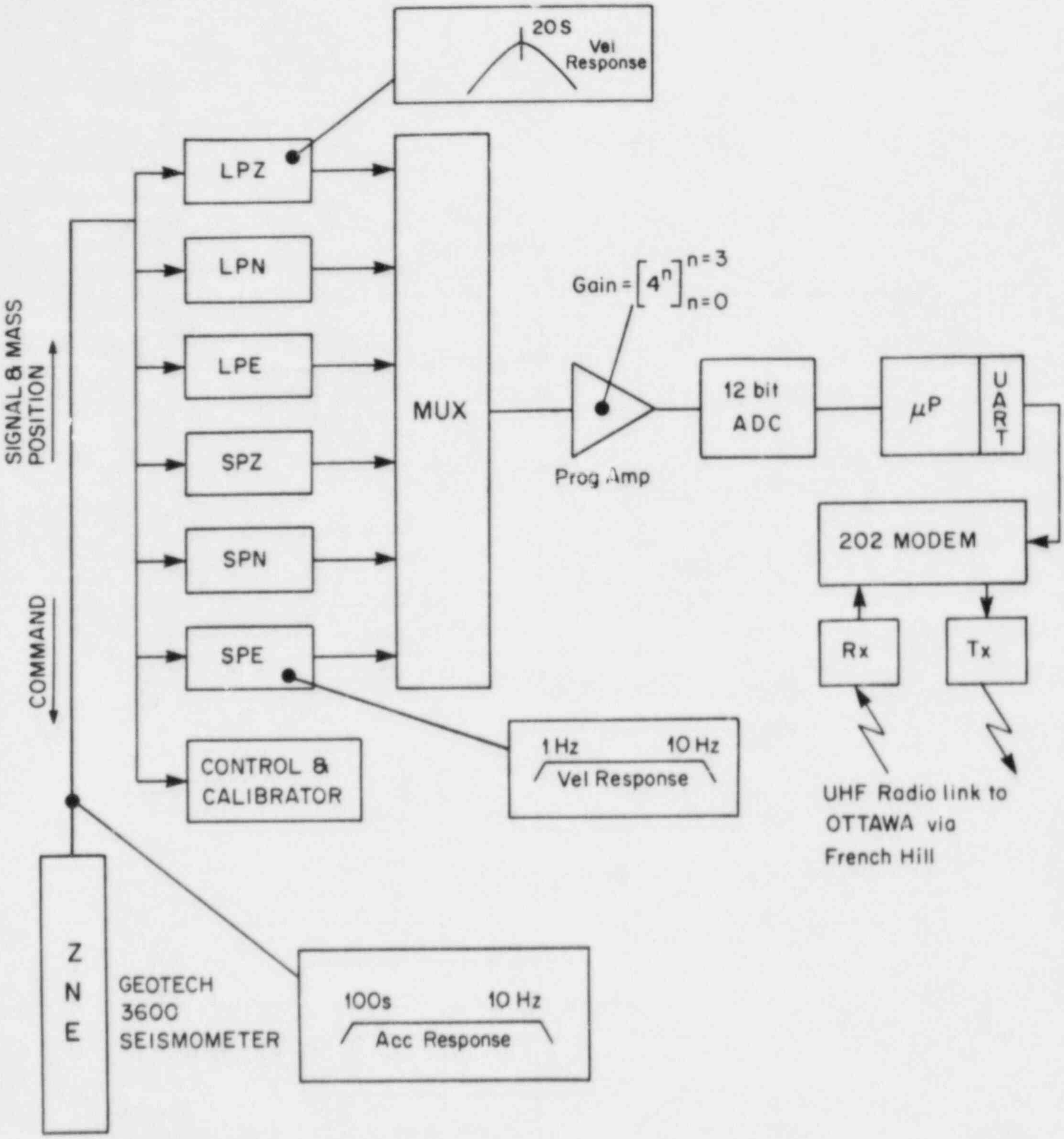


Figure 14. Block diagram: GAC station.

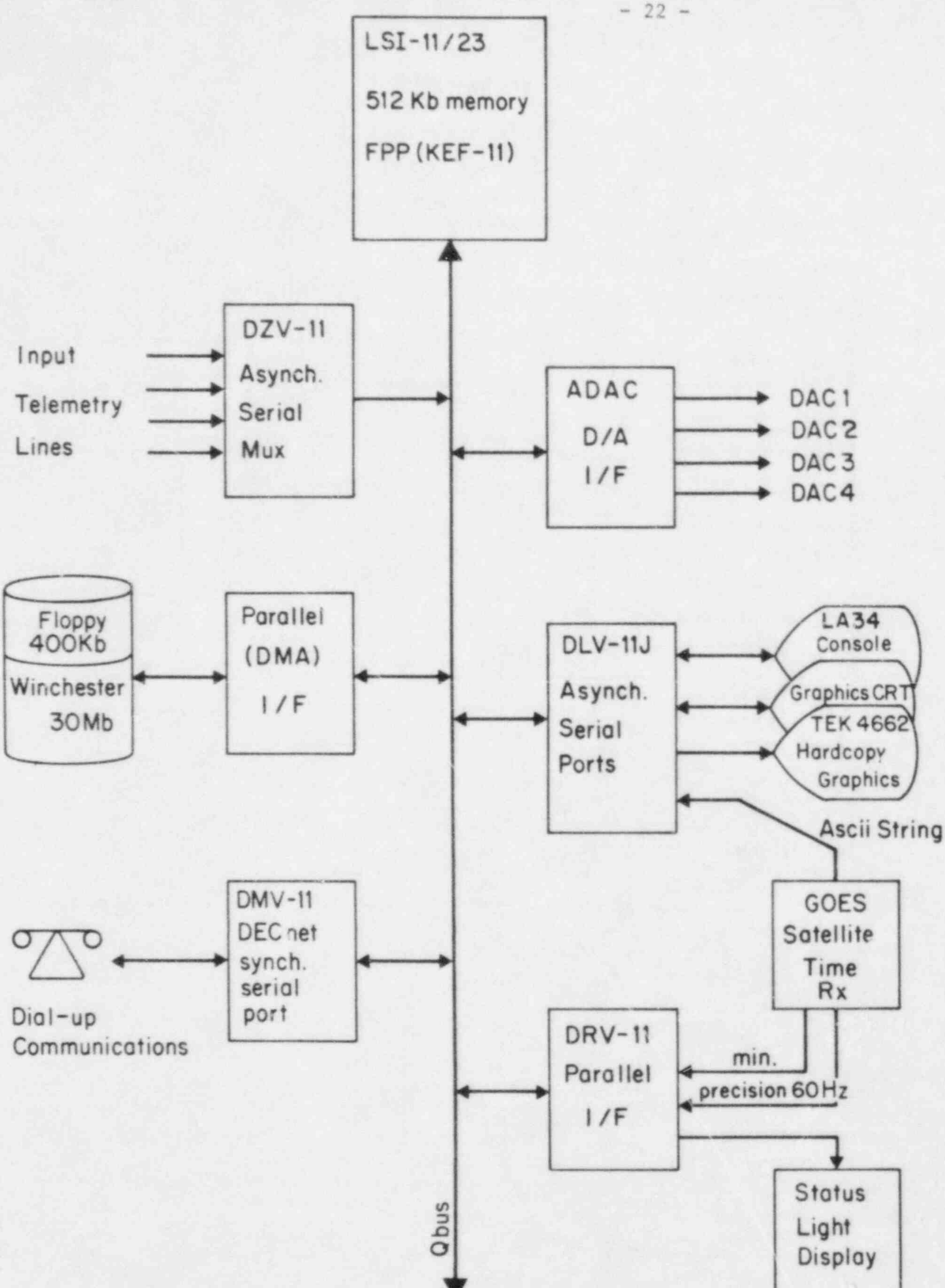


Figure 15. Block diagram: SUO station.

2.8 Overview of Datalab Hardware

The most general view of the datalab hardware is as shown in the block diagram of Figure 16 and the photograph of Figure 17. Figure 16 shows the connections between the data acquisition systems, the VAX data processing system, the user terminals, the tape archive and the dial-up remote processors. More detail on a typical event processor can be seen in the block diagram of Figure 18 and a further breakdown of the front-end communications processor is shown in the block diagram of Figure 19.

2.9 Datalab Data Flow

A block diagram showing the overall data flow is shown in Figure 20. Data bytes arriving from the various outstations are captured by hardware and saved in a 64 byte temporary storage (a silo). The front-end processor receives precision 60 Hz from the GOES clock and uses this to interrupt the input process at 60 Hz. The silo is then emptied into one of a pair of input buffers and time tagged. This process continues until a real-time second mark occurs, at which point, the buffers are swapped and the absolute time is written into the new input buffer. A background process then unscrambles the data in the recently filled input buffer recognizing the packet structure and using a Network Configuration Table to determine the correct format for the output buffer. The output buffer will thus contain a complete set of network data as acquired in the previous second ordered by station and component and tagged with absolute time. Missing data samples are flagged and counted and replaced with the most recent valid value. After the addition of a sum-check word for error checking, the one second buffer is transmitted to the host processor.

On receipt of the one second data blocks, the host processor immediately writes the data to the 5 minute ring buffer implemented in disc storage. The new data are also processed by the event trigger.

The ECTN event detector decimates the input stream by a factor of two and computes a running second difference to locate and average out single sample spikes. Next, two stages of recursive digital filtering implement a bandpass filter having a passband of 2-5 Hz. The absolute filtered values are integrated to form a short-term average with a 4.3 second time constant and a long-term average with a 4.3 minute time constant. A trigger is declared when the short-term average exceeds the long-term average by a specified threshold factor, typically 2 to 4. The event terminates when the short-term average again falls below the long-term average. Digital data from all channels in the network are saved in an event file on disc for every detected event, and an entry is made on the console typewriter log. The detection filter characteristics, time constant, and trigger threshold may each be changed onto a per channel basis to allow "tuning" the detector for events of interest.

A comprehensive set of utility programs are used for reporting errors, dumping buffers, rating the clock, modifying a configuration table and so on. A simple hardware "watchdog" is used to drive a set of "traffic light" indicator lamps. By regularly updating the watchdog, the monitor software can keep the green light on, indicating to the operator in a straight-forward manner, that all is well. Checks which are made include indicating remaining disk storage and correct program operation. Such a scheme is particularly useful during network operation out of normal office hours when a commissionaire, for example, can quickly determine the system status.

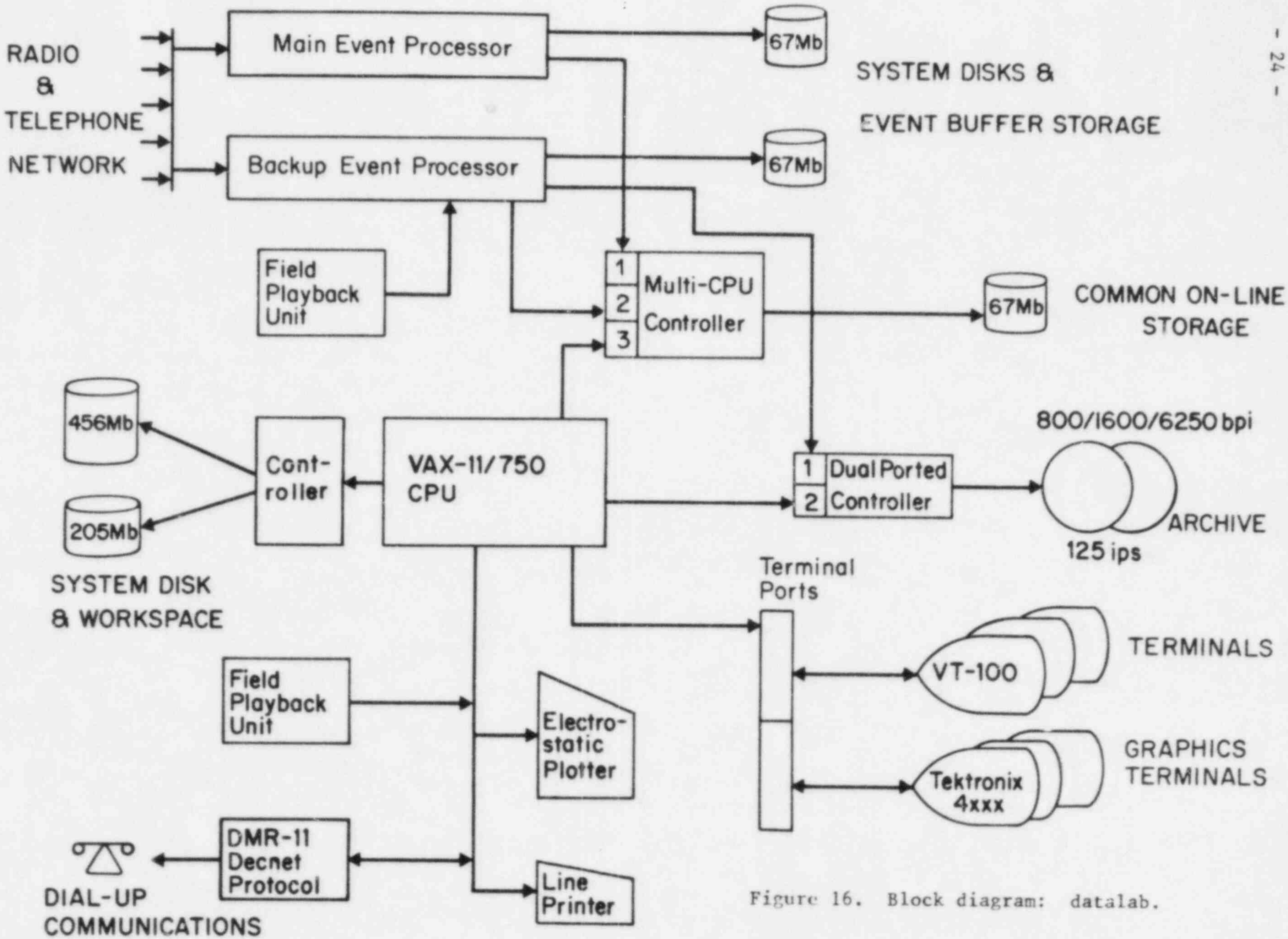
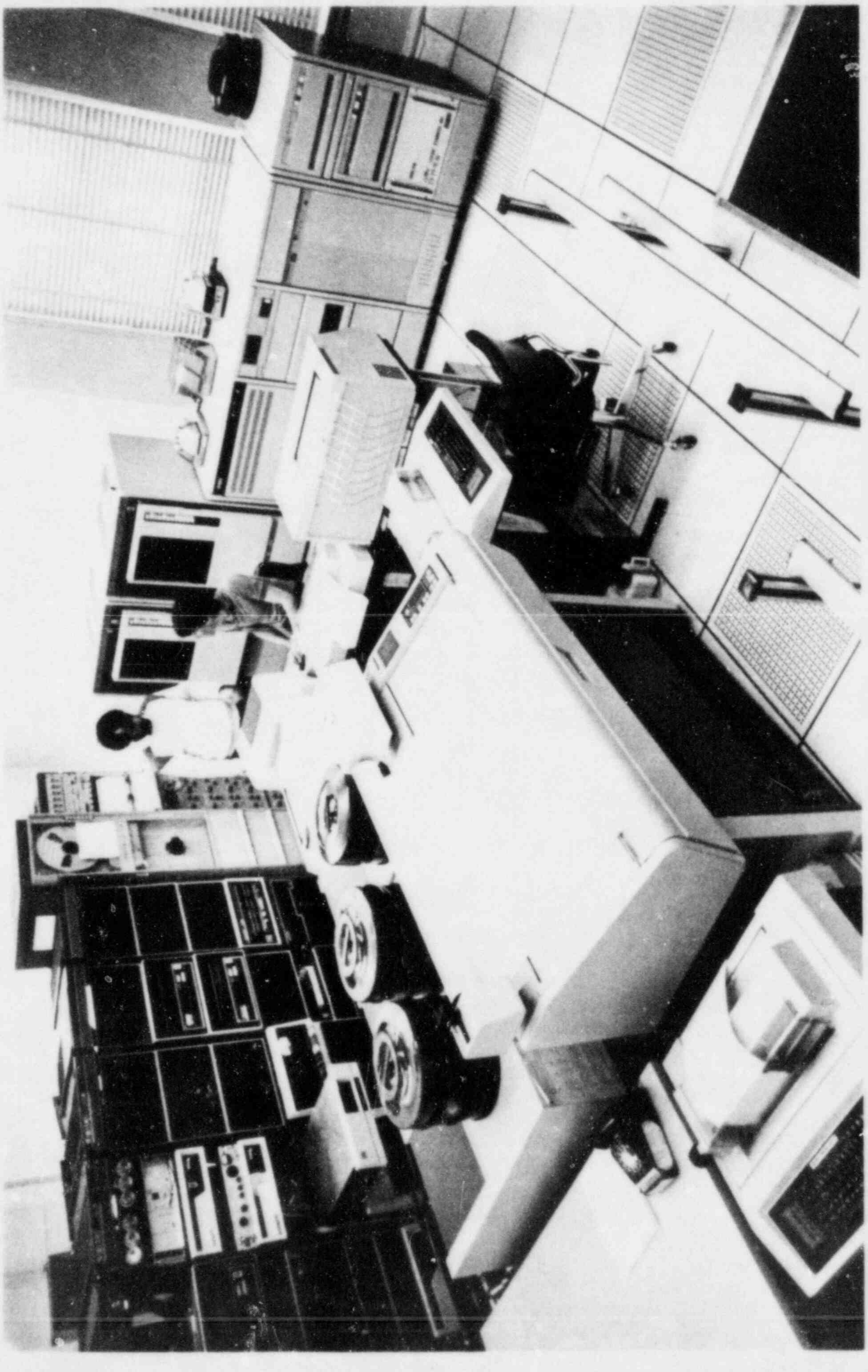


Figure 16. Block diagram: datalab.

Figure 17. Datalab



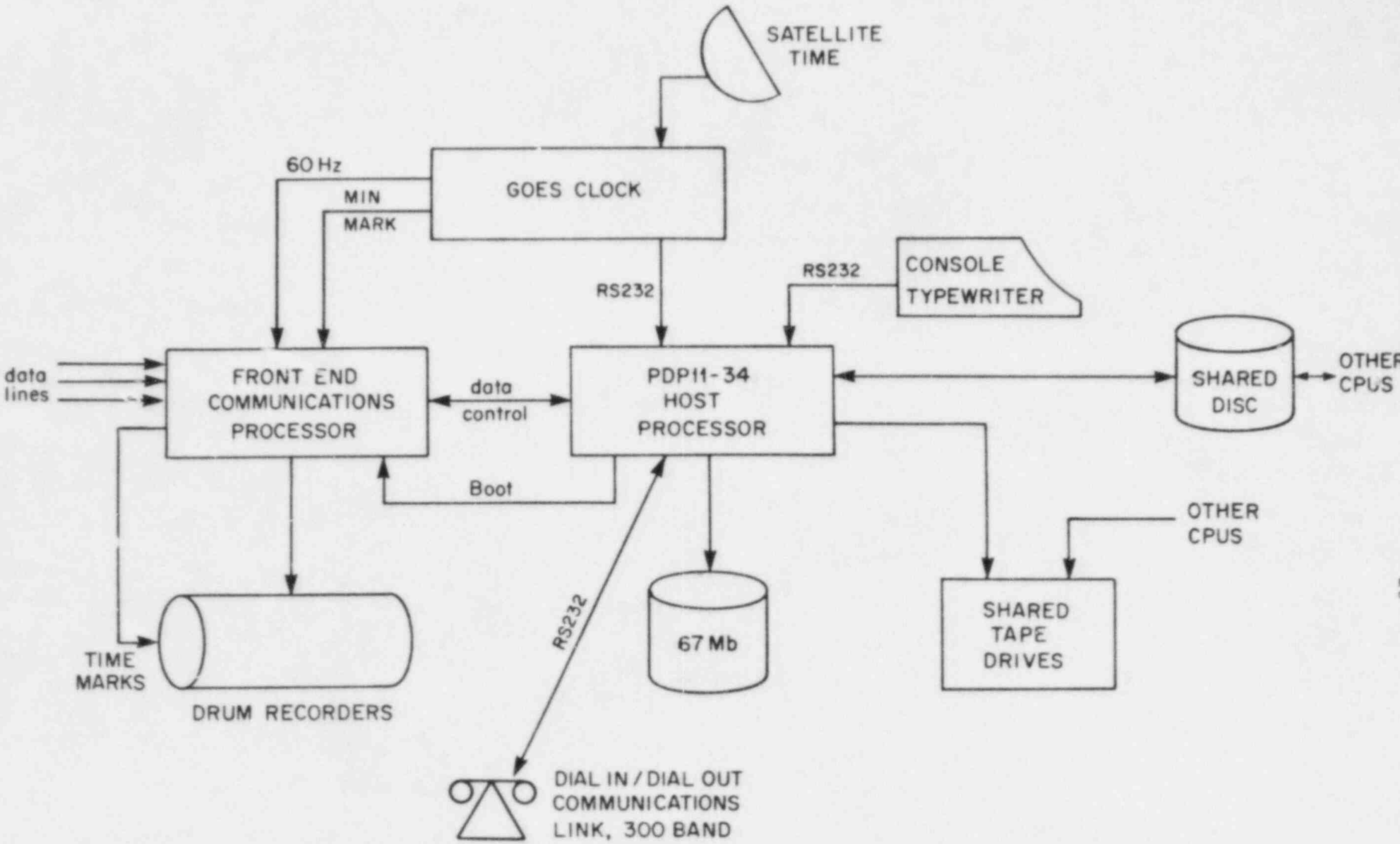


Figure 18. Block diagram: event processor.

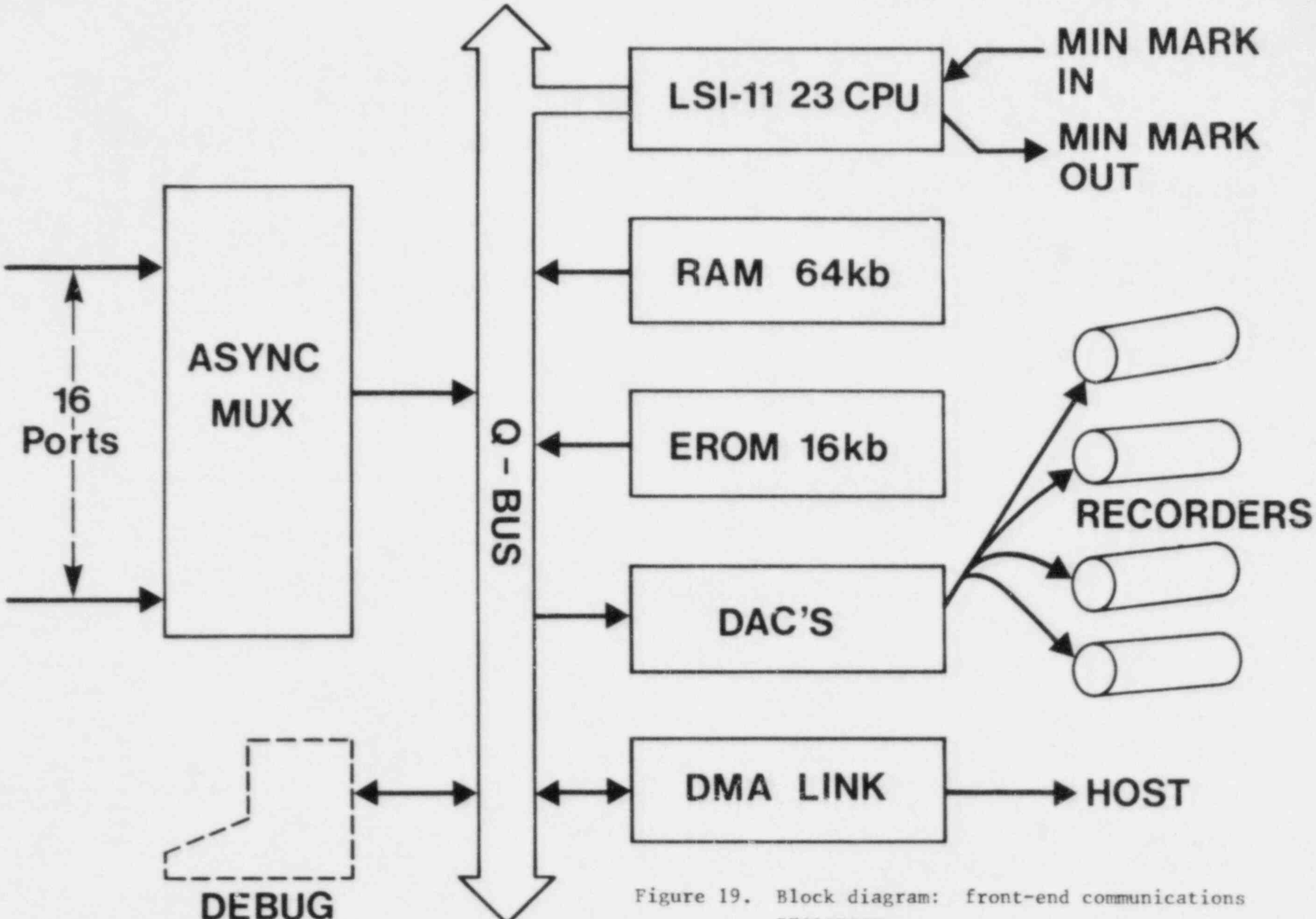


Figure 19. Block diagram: front-end communications processor.

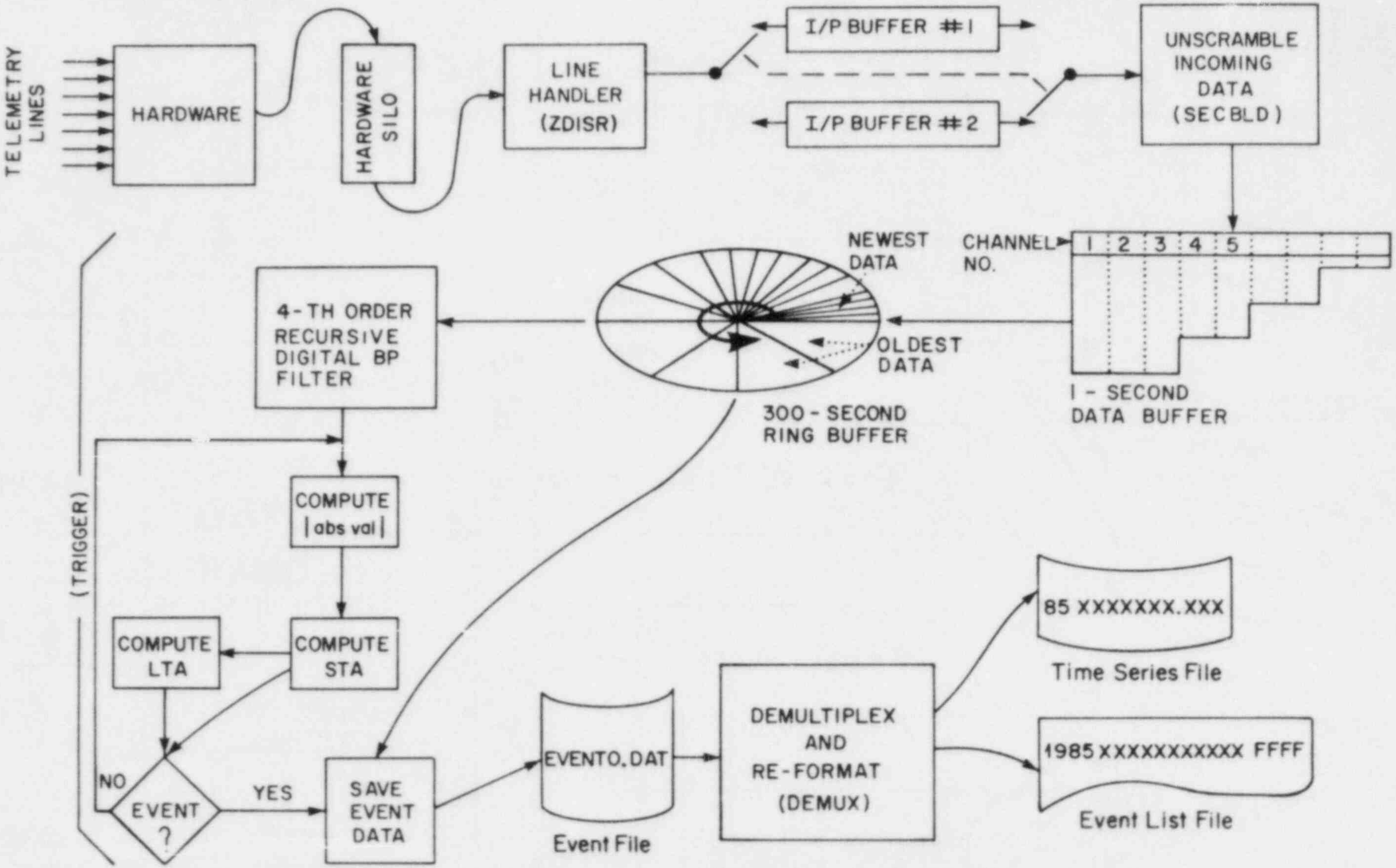


Figure 2C. ECTN data flow.

During the course of a day, a low priority background process completes the demultiplexing of the data to order them by station component in each event file. The demultiplexed data is copied to the shared event disc for subsequent processing and viewing.

A second data collection process operates in parallel with the event trigger to gather the long period data from GAC into a day file. Continuous GAC data goes into this file which is normally closed and the new one opened at 9 hours EST each day.

The central-site software is completely table driven. Most network configuration and system control parameters may be modified by editing a simple ASCII Network Configuration file, then running the configuration program. Changes to the front-end processor take effect on re-boot. In addition, a simple host/front end message exchange interface allows an operator to modify certain parameters in the front-end on-the-fly. For example, one of the fields in the configuration table is used to determine which of the station data are to be sent by the front-end processor to the drum recorders via digital-to-analog converters. Because of the processing delays, the drum recorders operate 2 seconds behind real time; however, since time marks are also dalayed, a valid record is obtained.

To permit flexibility in network reconfiguration, the program and more particularly, the network configuration table is downloaded from the host process on start-up and stored in read-write memory so that it can be easily modified by the operator. In the event that the front-end must be started up when the host is down, a back-up program and table are stored in ROM in the front-end. Making changes here is clearly much more tedious but is nevertheless possible.

Data from the Sudbury (SUO) remote processor are obtained on a daily basis by dial-up 9600 baud telephone link using the public phone network. The SUO event files are subsequently merged with the main ECTN files when they overlap (as from January 1985).

2.10 Data Analysis Facilities

The data analysis software runs on a VAX-11/750. Key elements are the electrostatic plotter for hard copy printout of signal traces, the graphics terminals and the high density tape drives for archiving the data. An interactive data analysis program with acronym "SAM" (Seismic Analysis Monitor) has been developed as a tool that seismologists use to:

- select events for interactive analysis;
- display time series traces and pick and name phases using a comprehensive set of screen commands;
- calculate epicentres utilizing both direct and refracted phases and a spherical earth model;
- merge data from overlapping event files into a single composite event file;
- archive and restore data to and from magnetic tape; and
- filter data as required.

2.11 System Performance

A key parameter in assessing the performance of any real-time seismic data acquisition system is its downtime. The downtime statistics for the network over the past five years are summarized in Table 2 and were determined by counting missed samples accumulated on a daily basis. Typical annual downtimes for outstations with telephone communications are of the order of 1% in the absence of specific problems. At the start of the period, comparable figures were obtained for the outstations using radio links, but in more recent years the reliability has deteriorated as a result of radio interference in the vicinity of Ottawa, and in particular at the radio repeater station at Camp Fortune. There is no easy solution to this problem because of congestion in the usage of the radio spectrum and because the most favorable radio repeater sites are also the most popular.

During the early years, a fully redundant processing system was not used and, on occasion, unacceptable data loss occurred (for example some of the largest Miramichi events in 1982). As a result, two essentially identical processors were set up to process all incoming data in parallel and create two independent event data sets. This fully redundant operation is used whenever an operator is not present in the data lab, principally weekends and evenings. When the system is working correctly the redundant data set is simply erased. In addition, both systems have been equipped with red-yellow-green traffic lights to give a simple unambiguous statement via the software on the state-of-health of each system.

In general, the reliability of the outstation hardware has been excellent with some sites operating for periods of several years without failure. As an example of the ruggedness of the equipment, the station at JAQ has operated in summer temperatures of 30°C and winter temperatures of -40°C without problems.

2.12 Data Archive

The ECTN archive contains digital waveform data commencing from July 1975, to the present. Earlier data, obtained during the initial development stages, have unfortunately become unreadable and have been discarded. At present, the archive holds approximately 4100 events, including local earthquakes, blasts, teleseisms, and calibrations. New data are accumulating at a rate of about 25 events per week.

Originally, the data were written in a plethora of different formats, reflecting changes in operating systems, application software versions, and the addition of new channels over the years. We are currently in the process of reading all the old data tapes and converting them to a standard format directly accessible by SAM. When this process is completed, the entire archive will comprise some forty 2400 foot tapes recorded at 6250 bits per inch density.

2.13 Discussion

The original decisions regarding bandwidth and sample rate are still appropriate in 1985. In retrospect, the Nyquist filter of the Mark I stations should have been retained since there is evidence of aliasing in some signal spectra as recorded in Mark II stations. The next generation of outstation (Mark III), which are planned, will have better aliasing protection.

TABLE 2. ECTN DOWNTIMES 1981-1984

Station	% Downtime by year				Radio or Telephone	Comments
	1984	1983	1982	1981	-	
Front end	0.1	0.0	0.00	0.4	-	Computer only
Host	0.2	0.2	0.05	0.2	-	Computer only
OTT	3.9	7.5	0.5	0.4	-	Direct connection
MNT	0.1	0.8	1.0	0.7	T	
MIQ	-	-	-	0.4	T	
MNQ	1.8	0.4	0.04	1.4	T	
GNT	7.0	5.7	0.5	0.1	T	
SBQ	0.1	0.0	1.1	3.8	T	
LPQ	9.0	5.4	18.2	1.2	T	
FHO	-	-	-	0.3	R/T	
JAQ KAQ LDQ	12.5	5.0	1.3	0.3	R/T	
WEO	5.8	1.1	0.0	-	T	
GAC SPZ	4.2	2.8	2.3	0.1	R	
VDQ	0.9	0.7	2.7	3.0	T	
WBO	17.8	5.8	0.2	0.4	R	Via Camp Fortune
CKO	31.8	5.7	2.4	3.0	R	Via Camp Fortune
TRQ	11.0	54.2	16.2	0.1	R	Via Camp Fortune
GRQ	10.3	23.3	22.6	0.1	R	Via Camp Fortune
GSQ	2.1	0.6	1.6	-	T	
EBN	4.3	0.9	1.8	-	T	
GGN	1.9	0.9	8.4	-	T	
LMN	12.7	11.2	32.3	-	T	
KLN	3.1	11.2	5.4	-	R/T	
HTQ	1.3	0.2	0.3	-	T	
EEO	2.1	-	-	-	T	

Differential signal amplification of the seismometer signal is considered both useful and essential. On two occasions, a poorly adjusted common mode rejection circuit has led to long period noise on the seismograms. This is interpreted as being caused by aliased 60 Hz line interference (aliased from 59.95 Hz to 20 seconds) and demonstrates the need to reject 60 Hz common mode signals.

The wide dynamic range has been useful. Figure 21 shows the seismogram recorded at Edmundston, N.B., some 138 km distant from a magnitude 5.4 Miramichi event of January 11, 1982. The maximum ground velocity was 1.06 mm/s, leaving about 20% headroom in remaining dynamic range. The inset in the upper left of the figure shows the early part of the seismogram aligned in time but magnified 200 times. Microseismic background is now apparent, as is fine detail of the initial onset.

The performance of some of the radio links operating in the vicinity of Ottawa has been disappointing. These performed well when first installed, but as the number of other UHF links has increased in the region, so have the number of dropouts in the data. Many different organizations now operate UHF radios and compete for the choice repeater sites located on a height of land with good road access and mains power. An example is the jumble of antennas at the Mont-St.-Marie repeater site (Figure 22). Another aspect with has proved troublesome has been time delays on the telephone communications network. This is now dealt with by performing end-to-end transit time calibrations and the procedure has become a part of the overall station calibration process. The measured delays are shown by station in Figure 23 and show good agreement with calculated delays shown on the same figure.

The issue of time delays has prevented the use of commerical asynchronous line multiplexers since the time delays through the multiplexers could not be guaranteed to be constant. An alternate solution would have been to synchronize the remote stations as has been done recently in Japan. In balancing the increased complexity and cost that would have been required to implement such a system against the benefits, we have chosen the present system which permits us to time events to within 0.1 second by allowing for communication delays (Table 3). Taking into account the minimum station separation and our knowledge of seismic velocities, this is considered to be an acceptable accuracy.

The provision of software tools to enable the data to be viewed and used has proved a time consuming task. Inevitably, there has been a steady stream of software changes required to cater for additional and different stations. Over the years, a determined effort has been made to separate parameters and code, so that networks could be changed by changing tables and not having to modify code. A significant effort is also required to accommodate changes and upgrades to the proprietary mini-computer operating systems. Despite good intentions to "freeze" the system, the new releases inevitably include some feature which is essential. Our increasing use of proprietary computer-to-computer communications products increases this problem since it links processors of different vintages into an organization-wide network which often requires operating systems to stay in lockstep.

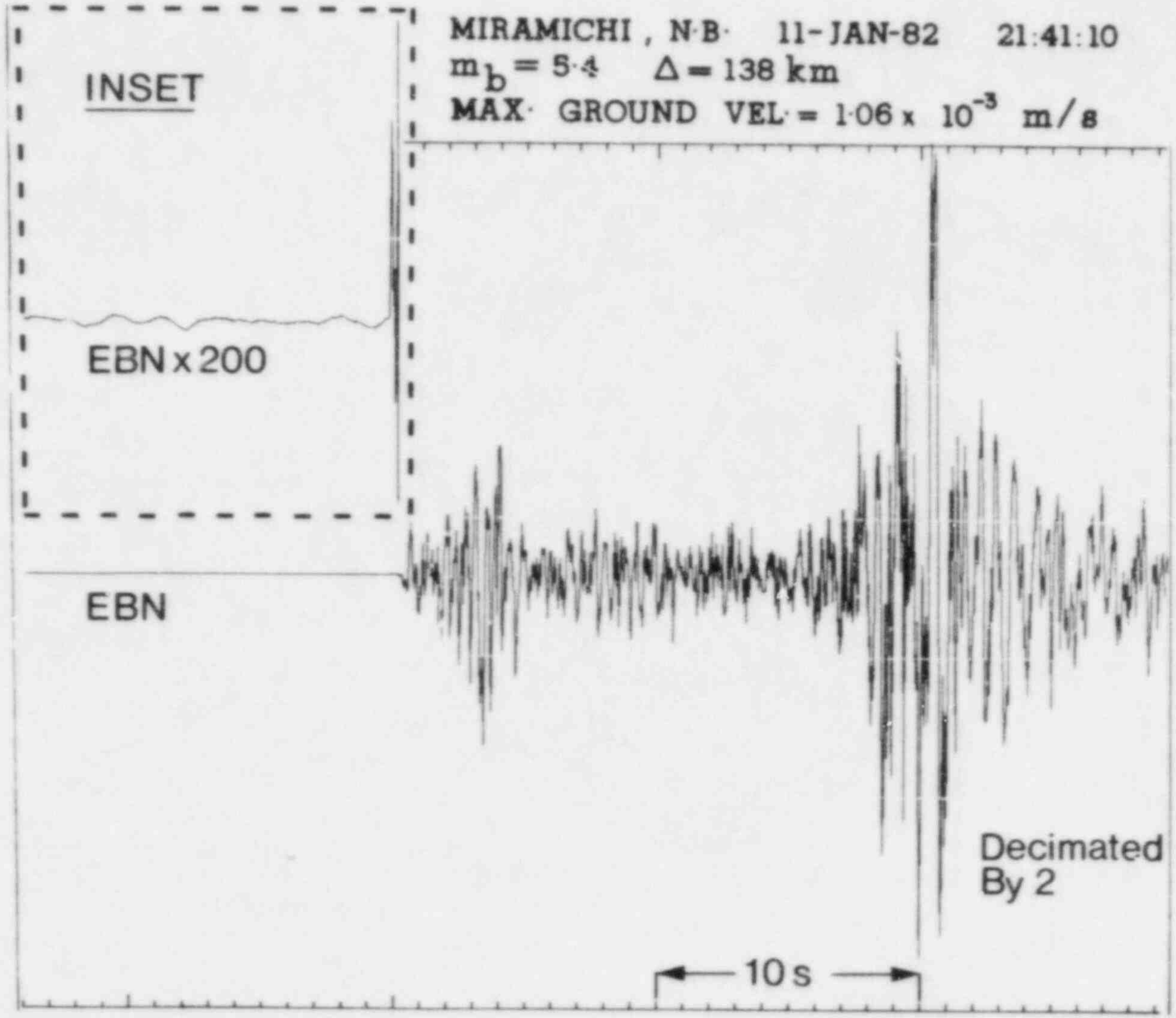
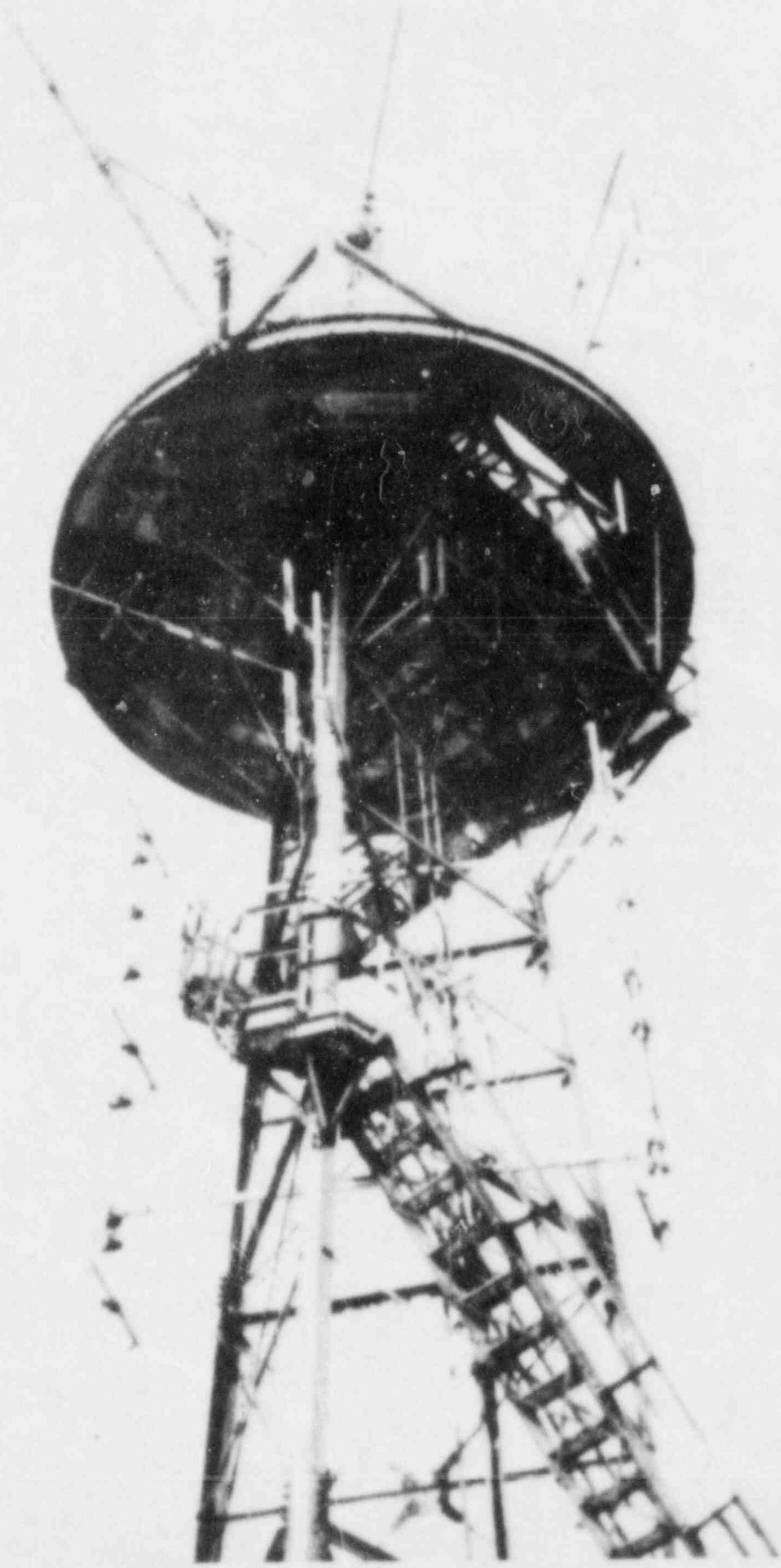


Figure 21. Seismogram of a Miramichi earthquake (M5.4) recorded at EBN.

F gure 22. Antennas at Mont St.-Marie



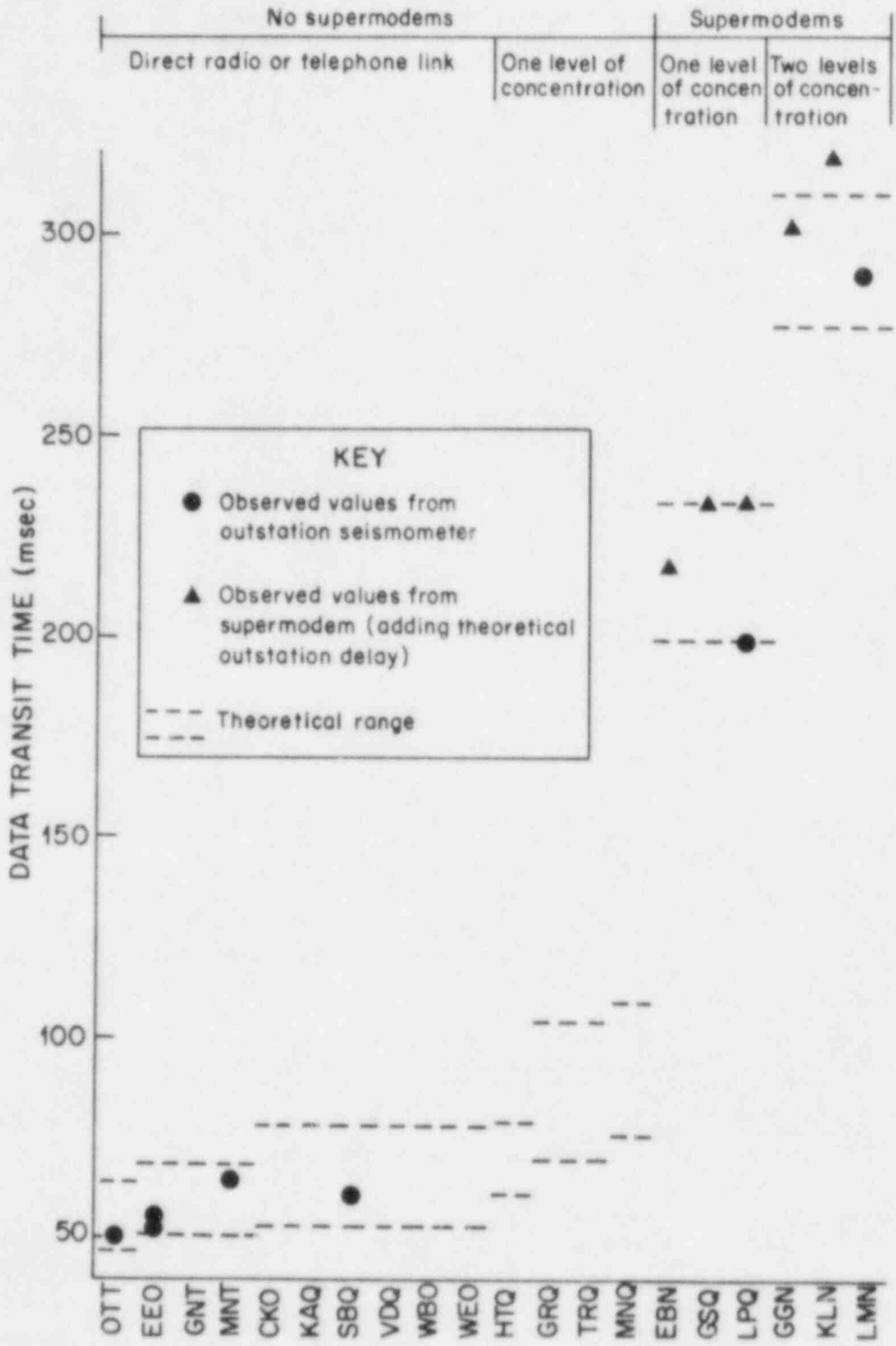


Figure 23. Theoretical and measured data transit times.

Table 3. Theoretical data transit times.

STATION	OUTSTATION DELAYS			TELEMETRY DELAY		CONCENTRATOR DELAYS				PDP-11	TOTAL	
	PREAMP	FIXED	VARIABLE	RADIO	TELEPHONE*	FIXED	VARIABLE	SUPERMODEM			MIN	MAX
								RDL	SJN			
OTT	30	1	0 to 16.7		-					16.2	47.2	63.9
EEO	30	1	0 to 16.7		4					16.2	51.2	67.9
GNT	30	1	0 to 16.7		5					16.2	52.2	68.9
MNT	30	1	0 to 16.7		4					16.2	51.2	67.9
CKO	31	5.7	0 to 16.7	0.6						16.2	53.5	70.2
KAQ	31	5.7	0 to 16.7		12					16.2	64.9	81.6
SBQ	31	5.7	0 to 16.7		8					16.2	60.9	77.6
VDQ	31	5.7	0 to 16.7		8					16.2	60.9	77.6
WBO	31	5.7	0 to 16.7	0.4						16.2	53.3	70.0
WEO	31	5.7	0 to 16.7		5					16.2	57.9	74.6
HTQ	31	5.7	0 to 16.7		9	16.7	0 to 16.7			16.2	61.9	78.6
GRQ	31	5.7	0 to 16.7	0.6		16.7	0 to 16.7			16.2	70.2	103.6
TRQ	31	5.7	0 to 16.7	0.6		16.7	0 to 16.7			16.2	70.2	103.6
MNQ	30	1	0 to 16.7		12	16.7	0 to 16.7			16.2	75.9	109.3
EBN	31	5.7	0 to 16.7		15.5	34.0	0 to 16.7	96.5		16.2	198.9	232.3
GSQ	31	5.7	0 to 16.7		15.5	34.0	0 to 16.7	96.5		16.2	198.9	232.3
LPQ	31	5.7	0 to 16.7		15.5	34.0	0 to 16.7	96.5		16.2	198.9	232.3
GGN	31	5.7	0 to 16.7		19.5	34.0	0 to 16.7	96.5	74.6	16.2	277.5	310.9
KLN	31	5.7	0 to 16.7		19.5	34.0	0 to 16.7	96.5	74.6	16.2	277.5	310.9
LMN	31	5.7	0 to 16.7		19.5	34.0	0 to 16.7	96.5	74.6	16.2	277.5	310.9

Note: * - inter-supermodem telephone delays included (Saint John (SJN) to Riv.-du-Loup (RDL) is 7 msec; Riv.-du-Loup to Ottawa is 9.5 msec).
- all table values are in milliseconds.

2.14 Future Plans

The differences between ECTN and the other Canadian seismograph networks become somewhat less distinct as the future is comtemplated. Plans are now being made to provide a full digital instrumentation for the Yellowknife Array, and to do the same for the array at Charlevoix. There are also plans to update the Canadian Standard Seismograph Network with broadband digital instrumentation. One of the major goals in our future plans is to standardize data formats and archive facilities so that the tools will be available to enable seismologists to access data from any of these networks.

There are currently no specific plans to increase the number of stations in the ECTN network proper. However, there is increasing enthusiasm to upgrade at least some of the outstations to provide three-component, short-period data. During 1985, the event detector computers will be replaced with modern high-performance machines occupying only one-quarter of the physical space. The availability of cheap memory will allow the 5 minute ring buffer to be implemented in memory as opposed to disc. The reduction in physical size coupled with improved technology should lead to higher reliability. Local area networks are being considered for efficiently passing bulk data between processors, and a commercial database system will be purchased to implement a more formal archive with appropriate access tools.

3. EASTERN CANADIAN EARTHQUAKES 1979-1984

3.1 Earthquake Data Reporting

In addition to an exchange of seismic data by telephone between EPB and northeastern U.S. seismograph network operators, which has been a regular practice for many years, under the terms of the Canadian Seismic Agreement EPB devised an ECTN Bulletin to make eastern Canadian seismic data available in advance of the preparation date of the Northeastern U.S. Seismic Network Bulletin. The ECTN bulletin was initially produced on a bimonthly schedule, but in January, 1983 was changed to quarterly to conform to the schedule of other Canadian national bulletins. The ECTN Bulletin is distributed to the USNRC and all northeastern U.S. network operators in a hardcopy format and, in addition, to the NEUSSN Bulletin compilers at Weston Observatory on magnetic tape. EPB also distributes to the same institutions other bulletins giving chronological lists of epicentres, magnitudes and other derived parameters of all earthquakes located in or near Canada.

3.2 Summary of Eastern Canadian Seismicity 1979-1984

Figure 24 is an epicentral plot of all earthquakes located in eastern Canada and adjacent regions of the northeastern U.S. from 01 January 1979 to 31 December 1984. During this six-year period there were 6 earthquakes of magnitude 5.0 and greater, 18 of magnitude 4.0 4.9 and 211 of magnitude 3.0 - 3.9. A summary of hypocentral parameters and epicentral intensity is given in Table 4 for all earthquakes of magnitude 4.0 and greater.

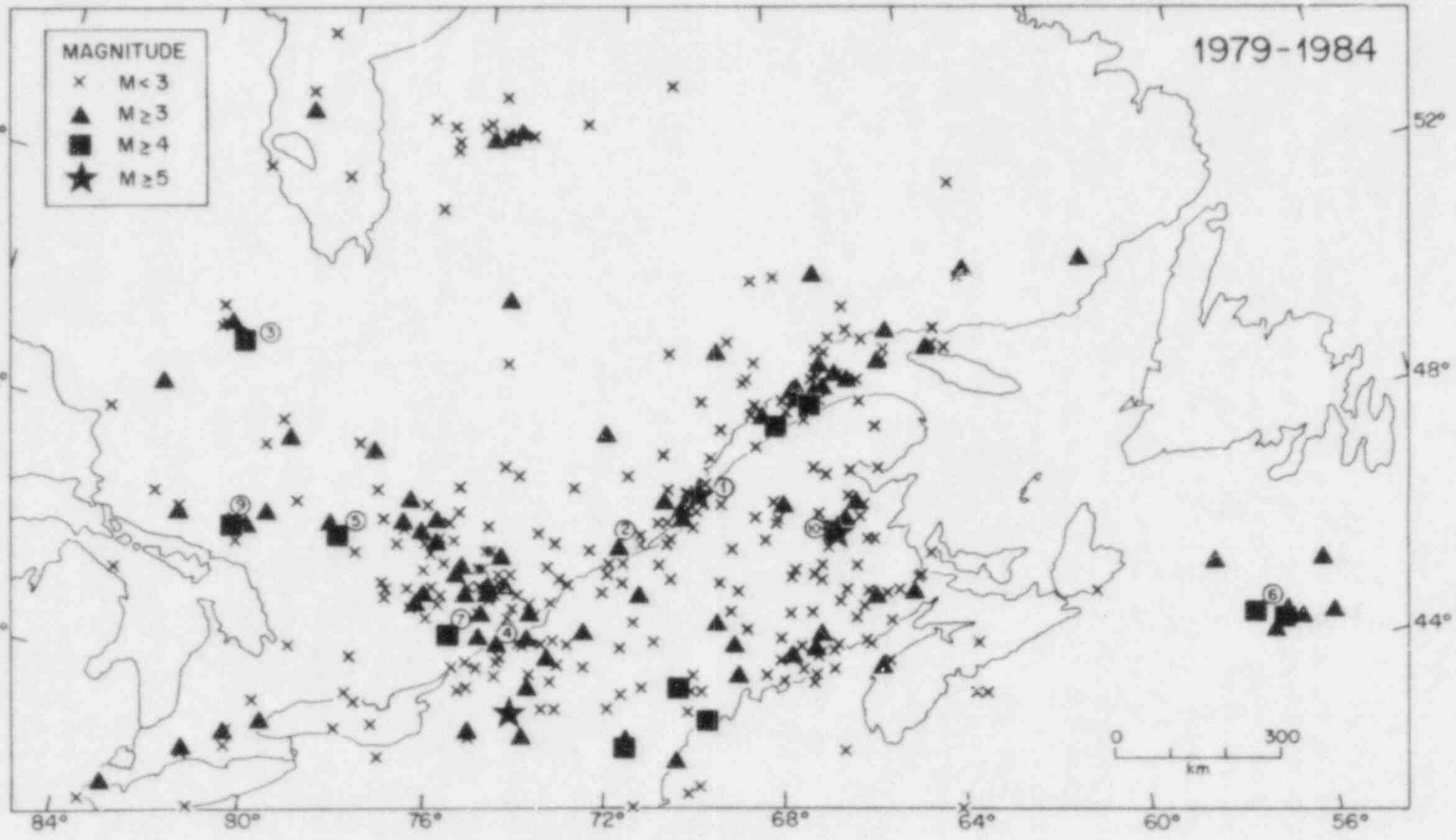


Figure 24. Epicentral Plot of all earthquakes in eastern Canada from January, 1979 to December 1984.

TABLE 4
Eastern Canadian Earthquakes M ≥ 4.0 1979-1984

Date	Time (UT)	Lat (°N)	Long (°W)	h (Km)	M	I_o
19 Aug 79	12:49:31	47.67	69.90	10	MLg 5.0	V
03 Apr 80	16:57:24	48.77	67.95	18(G)	MLg 4.0	IV
13 Apr 80	22:40:23	49.64	81.64	18(G)	MLg 4.1	IV
09 Jan 82	12:53:52	47.0	66.6	5(G)	m_b 5.7	V
09 Jan 82	16:36:45	47.0	66.6	5(G)	m_b 5.1	IV
11 Jan 82	21:41:03	47.0	66.6	5(G)	m_b 5.4	V
13 Jan 82	17:56:43	47.0	66.6	5(G)	MLg 4.0	III
31 Mar 82	21:02:20	47.0	66.6	5(G)	m_b 5.0	IV
02 Apr 82	13:50:12	47.0	66.6	5(G)	MLg 4.3	IV
11 Apr 82	18:00:53	47.0	66.6	5(G)	MLg 4.1	IV
18 Apr 82	22:47:21	47.0	66.6	5(G)	MLg 4.1	III
06 May 82	16:28:07	47.0	66.6	5(G)	MLg 4.0	III
16 Jun 82	11:43:30	47.01	66.95	7	m_b 4.7	IV
13 Aug 82	01:06:42	46.67	78.53	18(G)	MLg 4.3	IV
17 Jan 83	19:35:52	49.11	67.06	18(G)	MLg 4.1	IV
14 Mar 83	20:41:40	44.83	56.99	18(G)	M_L 4.0	-
11 Oct 83	04:10:55	45.20	75.75	13	MLg 4.1	IV
02 Feb 84	11:15:34	44.66	56.38	18(G)	M_L 4.2	-
06 Jul 84	17:24:52	46.54	81.17	1(G)	MLg 4.0	III

The most significant earthquake sequence occurred in the Miramichi region of north-central New Brunswick and is summarized separately in the following section. Most of the other earthquakes occurred in the recognized Western Quebec, Charlevoix and Lower St. Lawrence seismic zones which have experienced larger historical earthquakes and relatively high rates of recent smaller earthquakes. In the summary that follows, emphasis is placed on significant earthquakes that occurred outside these zones. References, which provide additional information, can be found in the Bibliography in Section 5. The location of each event is indicated in Figure 24.

(1) 19 August, 1979. This magnitude 5.0 earthquake was the largest in the Charlevoix zone since 1952. The local Charlevoix seismograph array permitted a hypocentre location at a depth of 10 km with an uncertainty of about 2 km in each coordinate. The earthquake was followed by a sequence of 11 aftershocks, magnitudes 0.4 - 3.0 in the following eight days. Seismic moment has been estimated as 1.5×10^{23} dyne-cm, average dislocation 12 cm, fault area about 3.5 km^2, and stress drop about 50 bars. (Hasegawa and Wetmiller, 1980).

(2) 11 March, 1980. This magnitude 3.7 earthquake near St-Basile, Québec, about 40 km west of Québec City, is significant because it occurred in a region of very poorly known historical seismicity and very minor previous recent seismicity. It produced a small zone of intensity V near the epicentre where minor and isolated damage was reported. (Wetmiller et al., 1983).

(3) 13 April, 1980. This magnitude 4.1 earthquake in northeastern Ontario, near Cochrane, was the largest in this region since 1928. It occurred along the eastern side of the Kapuskasing Structural Zone. This region has been seismically more active since 1968 than the area of the 1935, magnitude 6.2, Timiskaming earthquake, indicating that the Kapuskasing Structural Zone may be undergoing contemporary tectonic adjustments. (Forsyth et al., 1983).

(4) 04 July, 1981. This magnitude 3.7 earthquake near Cornwall, Ontario, occurred 30 km northeast of the epicentre of the 1944 Cornwall-Massena earthquake. It produced a small zone of intensity V near the epicentre. A field survey located aftershocks with depths near 13 km. (Drysdale et al., 1984).

(5) 13 August, 1982. This magnitude 4.3 earthquake near Timiskaming, Québec, was the largest in this area since the 1935 earthquake. It produced maximum intensity IV near the epicentre (Drysdale et al., 1985).

(6) 14 March, 1983, 02 February, 1984. These magnitude 4.0 and 4.2 earthquakes are representative of the continuing activity near the Laurentian Slope south of Newfoundland, in the epicentral region of the 1929 "Grand Banks" earthquake. The most recent magnitude 5 earthquake in this zone occurred in 1975.

(7) 11 October, 1983. This magnitude 4.1 earthquake 20 km south of Ottawa, felt with maximum intensity IV, caused considerable public interest because it occurred four days after the magnitude 5.1, Goodnow, New York, earthquake which was also felt with intensity IV in the Ottawa area. Aftershock field surveys indicate a focal depth of 13 km. Mechanism analysis (R. Wahlstrom, in preparation) indicates thrust faulting due to north-south compression.

(8) 11 February, 1984. This magnitude 3.9 earthquake, 25 km northwest of Sioux Lookout, Ontario, occurred in a region of no known previous seismicity. A thorough investigation of the possibility that this event may be related to mining activity has led to the conclusion that it is a natural occurrence, and therefore the largest known earthquake in Ontario west of longitude 85°W. (This event is off the map area of Figure 24.)

(9) 06 July, 1984. This magnitude 4.0 event was a rockburst (induced earthquake?) in the Creighton mine near Sudbury, Ontario. Mechanism analysis for this and other large rockbursts in Ontario mines in 1984 by Welmiller and Cajka (in preparation) indicates that rockbursts are dominated by normal fault motion, opposite to the general thrust motion observed for earthquakes in the region.

3.3 Miramichi, New Brunswick, Earthquake Sequence

The Miramichi, New Brunswick, earthquake sequence that began on January 9, 1982 (No. 10 in Figure 24) and which had an aftershock sequence that continues at the time of writing (March, 1985), has been the subject of numerous investigations by EPB and other Canadian and U.S. researchers. A bibliography of EPB research reports is given in Section 5.5. A summary of this research (to early 1984) is given in the paper by Basham and Adams (1984); this paper is attached as an appendix to this report. In the following paragraphs we provide brief summaries of additional work that has taken place during the past year.

Seismic activity in the aftershock zone of the January 9, 1982 M5.7 Miramichi, New Brunswick earthquake was recorded by a joint EPB-USGS field survey from July 5 to 23, 1983. One hundred and seven microearthquakes, $M \leq 1.9$, and two calibration explosions were analyzed by means of precise hypocentre locations, composite P-nodal mechanisms and wave form modelling. The best fit P-velocity profile to the calibration shots was used for calculating hypocentral locations. It was a 0.5 km thick layer of 5.4 km/sec overlaying a half space of 6.0 km/sec. This model fits the explosion travel times at 27 sites from 0.5 to 39 km epicentral distance with an RMS error less than 0.03 sec. This model was supported by the observation on the earthquake seismograms of a near surface SV to P converted phase and by the lack of an obvious later converted or reflected phase from possible deeper velocity discontinuities down to 10 km depth. The earthquakes were initially located using this model and then re-located using a multiple master event technique and/or a joint hypocentre technique; absolute location errors are less than 2 km for 70% of the events studied.

Eighteen months after the main shock, the persistent aftershock activity was divided into five distinct and separate clusters, four associated with the original aftershock zone and one displaced 5 km northwest from it (Figure 25). The displaced aftershocks began abruptly only in May, 1983 and may be evidence of expanding long term stress changes caused by the earthquakes. Only three of the clusters were well enough covered by the field network to determine composite P-nodal mechanisms. The mechanisms are all nearly pure thrust mechanisms, with north-trending nodal planes dipping from 50° to 70°.

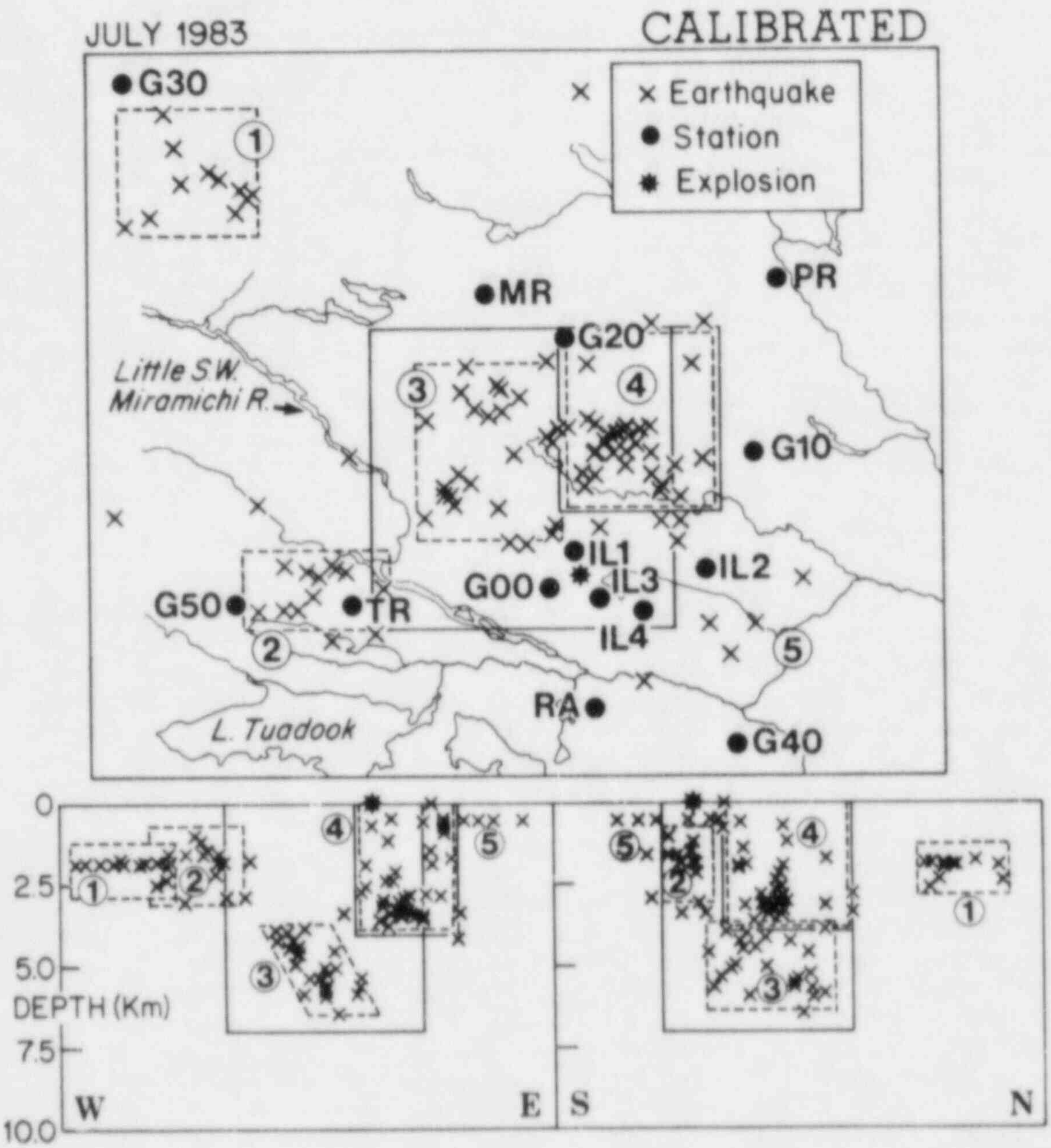


Figure 25. Miramichi earthquake activity recorded by the joint EPB - USGS field program in July, 1983. All events are smaller than M 2.0, many smaller than M 0. Solid boxes show extent of the aftershock zones in 1982; dashed lines show the 5 distinct clusters of activity found in 1983.

Inside the original aftershock zone, the long term activity appeared to be a simple continuation of the activity associated with the January 11, 1982 M5.4 and the March 31, 1982 M5.0 principal aftershocks. Activity directly associated with the main shock rupture plane was not immediately apparent, but the distribution of activity on the east side of the aftershock zone where the main shock occurred was not simply planar, possibly because the main shock and the March 31 aftershock were not co-planar events. Outside the aftershock zone, information for the one cluster where good data existed, suggested that the cluster was occurring along a north-trending thrust zone, a zone that has not been associated with any of the principal events of the sequence, and possibly represents seismicity induced on pre-existing fractures by long term stress changes following the principal events.

Overburden has been removed for 3000 m^2 around the 25 mm bedrock thrust found after the Miramichi earthquakes. The thrust occurred on a joint, not a distinctive fault plane, and proved less than 5 m long and probably less than 1 m deep. Its origin as a stress-relief feature was confirmed by a buckle that occurred overnight, two weeks after the cleanup ended. The new buckle trends 010°, similar to the thrust joint, and indicated the release of about 5 MPa of E-W stress. Overburden removal amounting to only 0.30 MPa triggered the buckle. During the summer of 1984 many further buckles occurred. Horizontal compressive stress of -2 to +16 MPa have been measured by Ontario Hydro in two 30 m holes on the outcrop. The show a wide scatter in stress magnitude and direction, suggesting that the near-surface is partly decoupled from regional stresses. The regional trend is NE to ENE compression, and is in reasonable agreement with the E-W compression shown by the stress-reflief features and by P-nodal solutions for the earthquakes.

In August 1984, a 1300-m trench (2 km NE of the thrust joint) was dug across the probable outcrop of the 1982 fault. Four places in the partly-excavated trench show fresh bedrock cracks (Figure 26). The largest is an open (tensional) crack 60 mm wide, 1.2 m deep, and striking 030°; other open cracks strike 030° to 110°. The 030° cracks parallel one P-nodal fault plane. The tensional cracks are thought to represent further evidence of near-surface stress changes caused by the 1982 earthquakes. The earthquake apparently caused complicated near-surface stress adjustments involving both compression and dilatation; as yet none of the cracks can be directly related to surface faulting.

3.4 EPB Research on Eastern Canadian Earthquakes 1979-1985

In order to provide for the USNRC and other readers of this report, a fairly complete record of EPB research activities on eastern Canadian earthquakes during the term of the Canadian Seismic Agreement, the bibliography in Section 5 contains a reference list of EPB research publications for the time period 1979-1985. The bibliography is sub-divided into the following six categories: seismicity summaries; seismic risk and zoning; strong ground motion; Charlevoix seismic zone; Miramichi, New Brunswick earthquakes; and focal parameters and seismotectonics.

Figure 26. Detail of fresh open crack uncovered in the 1300 m trench in Miramichi. This crack is typical of the fresh tensional cracks uncovered in the granite bedrock at this part of the trench. Long axis of compass points true north and ruler is 300 mm long. Pencil lies parallel to a pre-existing joint. The tensional crack partly follows the joint, but also deviates to break fresh rock. Because of their freshness, and lack of compacted fill, this and other similar cracks on the outcrop are attributed to the 1982 Miramichi earthquake sequence.

4. EASTERN CANADIAN STRONG MOTION NETWORK

4.1 Canadian Strong Motion Networks

The EPB has installed, and currently operates and maintains the strong motion seismograph network in western Canada. The National Research Council of Canada (NRCC) has installed and, until 31 March 1985, operated the strong motion seismograph network in eastern Canada. In addition in eastern Canada, there are strong motion instruments installed in hydroelectric dams and at a nuclear power plant reactor building that are maintained by the owner agencies with training and technical assistance from the NRCC.

Following the Miramichi, New Brunswick earthquakes of January, 1982, the EPB acquired five strong motion seismographs and the USNRC loaned the EPB five strong motion seismographs. A network of 8 instruments was deployed in the Miramichi epicentral area. Under the terms of the new Canadian Seismic Agreement, these USNRC seismographs have been transferred to EPB for deployment as described below.

4.2 Eastern Canada Network Configuration

The Charlevoix seismic zone in the lower St. Lawrence valley is considered, by Canadian and United States seismologists alike, to be the most likely site of a large eastern earthquake within a short time frame. Thus, the EPB plans to utilize funds provided through the Canadian Seismic Agreement to install additional strong motion seismographs in and near the Charlevoix seismic zone, and to operate and maintain these and the former NRCC stations as a consolidated network.

The eastern Canada strong motion network is shown in Figure 27 and the station sites are described in Table 5. The instruments at sites 1 to 9 were installed between 1966 and 1982, except for site 4 (Ottawa) which is now the EPB seismograph vault instead of the NRCC laboratory. Sites 19a to 19d are the four instruments that remain in the epicentral region of the Miramichi, New Brunswick, earthquakes.

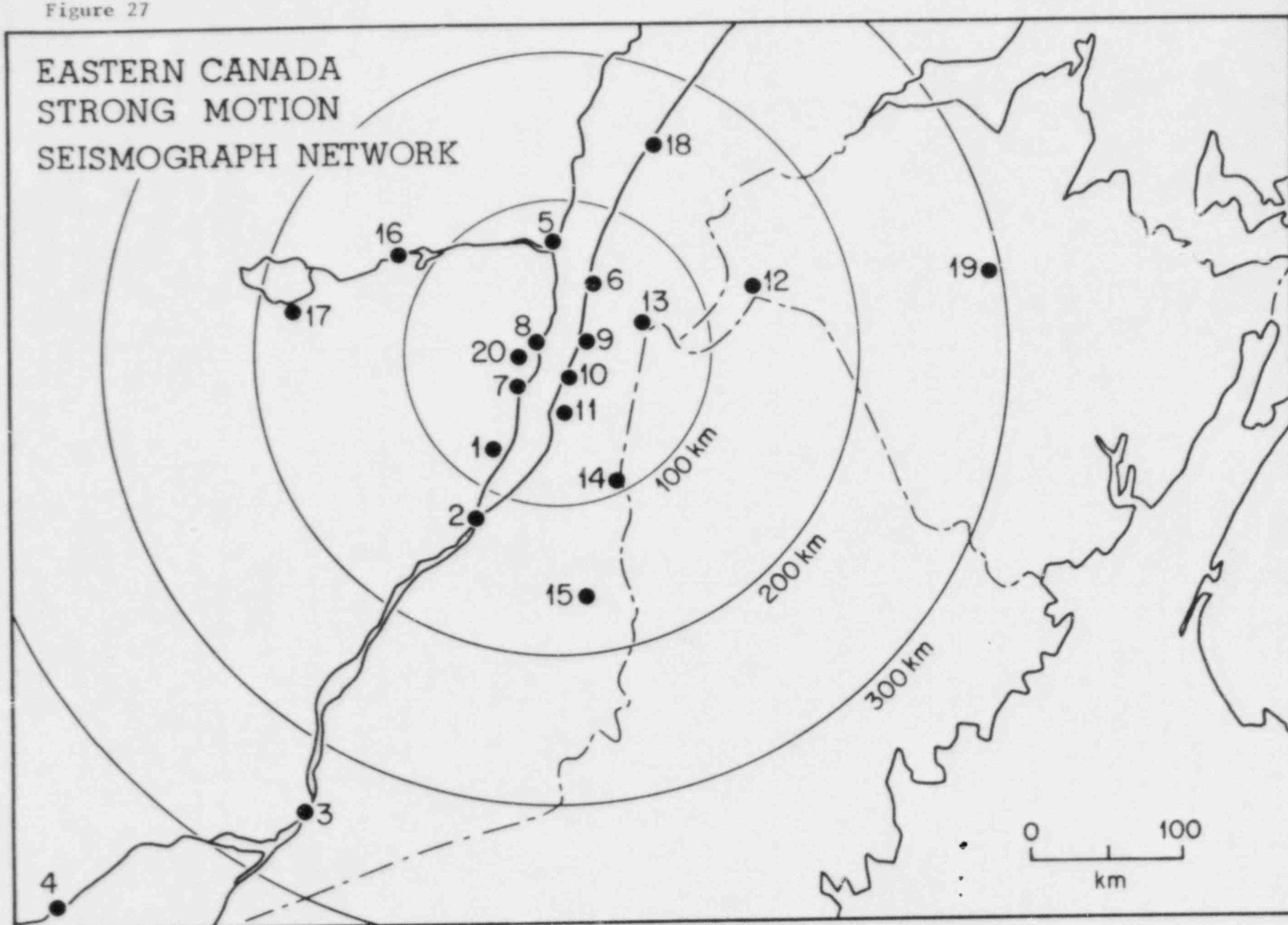
During August and September, 1984, new installations were made at sites 10-18. Seven of these sites are above ground seismic vaults in bedrock (free field), sited to avoid to the degree possible any cultural or industrial activity. The other two are on bedrock beneath one- and two-story woodframe buildings. Trigger levels of these SMA-1 instruments have been set at (nominally) 0.01 g. The actual values are given in Table 5. Five of these new sites have TCG-1B time code generators.

4.3 Plans for 1985

During 1985 it is planned to make installations at four sites. SMA-1's with time code generators will replace the AR-240's at sites 8 and 9 (La Malbaie and St-Pascal, Québec). SMA-1's with time code generators will be installed at the EPB Charlevoix Observatory (site 20) at Les Eboulements, Québec, and at one additional site to be determined. Time code generators will also be installed at all other sites in the network, except at Montreal (site 3) and Ottawa (site 4) which are co-located with ECTN stations.

Three of these instruments are to be removed from the Miramichi, New Brunswick, region, leaving one instrument at site 19. This plan is based on the assumption that no additional significant aftershocks will occur in Miramichi. Should one occur, the 1985 plan will be modified as necessary.

Figure 27


EASTERN CANADA
STRONG MOTION
SEISMOGRAPH NETWORK
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19
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0
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km

TABLE 5. Eastern Canada Strong Motion Seismograph Network (March, 1985)

No.	LOCATION	DATE	COORD	INSTR.	SENS	TRIGGER	BUILDING	FOUNDATION
1.	St-Féréol, Que.	1/66	47.12°N 70.83°W	SMA-1 TCG-1B	1 g	0.0072 g	Underground seismic vault. Instrument on concrete pier.	bedrock
2.	Québec, Que.	6/67	46.78 71.28	SMA-1	1/2 g	0.0073 g	Three-storey reinforced concrete. Instrument on concrete pier on basement floor slab.	bedrock
3.	Montréal, Que	12/73	45.50 73.62	SMA-1	1/2 g	0.0058 g	Four-storey steel frame, curtain wall, poured concrete. Instrument in seismic vault in basement.	bedrock
4.	Ottawa, Ont.		45.394 75.717	SMA-1			On pier in Ottawa seismograph vault.	bedrock
5.	Tadoussac, Que.	5/79	48.15 69.72	SMA-1 TCG-1B	1 g	0.0075 g	Concrete pier to bedrock in crawl space of one-storey building.	bedrock
6.	Rivière-du-Loup, Que.	6/80	47.82 69.53	SMA-1 TCG-1B	1 g	0.01 g	Two-storey reinforced concrete. Instrument on basement slab	bedrock
7.	Baie-St-Paul, Que.	10/82	47.45 70.50	SMA-1	0.5g	0.0079 g	Two-storey brick building. Instrument on basement slab.	alluvium valley
8.	La Malbaie, Que.	9/67	47.68 70.15	AR-240	1 g	0.5 mm	One-storey steel frame, masonry walls. Instrument on concrete pier on basement floor slab.	bedrock
9.	St-Pascal, Que.	10/69	47.52 69.80	AR-240	1 g	0.5 mm	One-storey reinforced concrete and masonry. Instrument on concrete basement floor slab.	bedrock
10.	Rivière-Ouelle, Que.	8/84	47.476 69.996	SMA-1 TCG-1B	1 g	0.0108 g	Above ground seismic vault.	bedrock

TABLE 5. (continued)

No.	LOCATION	DATE	COORD	INSTR.	SENS	TRIGGER	BUILDING	FOUNDATION
11.	St. Aubert, Que.	8/84	47.220 70.153	SMA-1 TCG-1B	1 g	0.0904 g	Crawl space beneath one-storey wood frame house	bedrock
12.	Edmundston, N.B.	8/84	47.462 68.241	SMA-1 TCG-1B	1 g	0.0103 g	Above ground seismic vault	bedrock
13.	St.-Éleuthère, Que	8/84	47.495 69.363	SMA-1	1 g	0.01 g	Above ground seismic vault	bedrock
14.	Ste.-Lucie-de-Beauregarde, Que.	8/84	46.741 70.017	SMA-1 TCG-1B	1 g	0.0100 g	Above ground seismic vault	bedrock
15.	St.-Georges, Que.	8/84	46.140 70.580	SMA-1 TCG-1B	1 g	0.0132 g	Above ground seismic vault	bedrock
16.	Chicoutimi-Nord, Que.	9/84	48.490 71.012	SMA-1	1 g	0.0108 g	Outcrop in basement of two-storey wood frame house.	bedrock
17.	St.-André-du-Lac-St.-Jean, Que.	9/84	48.325 71.992	SMA-1	1 g	0.0105 g	Above ground seismic vault	bedrock
18.	Rimouski, Que.	8/84	48.445 68.482	SMA-1	1 g	0.0101 g	Above ground seismic vault	bedrock
19a	Miramichi, N.B.	2/82	46.993 66.597	SMA-1 TCG-1B	1 g	0.0063 g	Above ground seismic vault	bedrock
19b	Miramichi, N.B.	2/82	47.034 66.612	SMA-1 TCG-1B	1 g	0.0054 g	Above ground seismic vault	bedrock
19c	Miramichi, N.B.	2/82	47.006 66.547	SMA-1 TCG-1B	1 g	0.0050 g	Above ground seismic vault	bedrock
19d	Miramichi, N.B.	2/82	46.946 66.595	SMA-1 TCG-1B	1 g	0.0065 g	Above ground seismic vault	bedrock
20	Les Eboulements, Que.	(1985)		SMA-1 TCG-1B			EPB Charlevoix Observatory, underground vault	

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The Miramichi, New Brunswick Earthquakes: Near-Surface Thrust Faulting in the Northern Appalachians

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Introduction

On January 9, 1982, in the unpopulated Miramichi Highlands of north-central New Brunswick, the largest earthquake in eastern Canada in thirty-eight years occurred. The recordings of this earthquake and its subsequent large aftershocks by modern global seismographs and accompanying field investigations have provided the most extensive data set ever captured for a potentially damaging eastern North American earthquake. This article will describe the sequence of earthquakes, summarize the results of investigations achieved to date by the Earth Physics Branch and by other Canadian and U.S. workers, and speculate on possible geological interpretations of the activity.

Earthquake History of New Brunswick

The decade of seismicity in the New Brunswick region (1970-1981) prior to January, 1982 is shown as an epicentre map in Figure 1, superimposed on the regional geology (adapted from Williams, 1978). None of these earthquakes exceeded a magnitude of 4. No obvious correlations can be seen between the epicentral patterns and the mapped geology and faults. Indeed, the pattern of epicentres in the western two thirds of New Brunswick and eastern Maine appears to be random. The cluster of activity in the top left corner of the map is associated with the active Charlevoix zone in the St. Lawrence Valley (Anglin, 1984). Only the earthquakes in this zone with epicentres on the south shore are shown. A small concentration of epicentres near the southern New Brunswick-Maine border may be associated with the Oak Bay Fault (Rast *et al.*, 1979) or with the local downwarp in the regional postglacial uplift that has been identified in the region of Passamaquody Bay (Barosh, 1981).

The largest earthquakes known in New Brunswick prior to 1982 occurred in 1855, 1869, 1904, 1922 and 1937 (Fig. 1). Isolated minor damage was reported for each of these earthquakes. The epicentres have been estimated from an analysis of reported effects and are uncertain by at least 50 km (the radius of the circles in Fig. 1). Magnitudes of approximately 5 for 1869 and 1904, and 4.5 for 1855, 1922 and 1937 have been inferred from estimates of the total felt area (A.E. Stevens, unpublished report, 1975). The magnitude of the 1937 event is supported by available instrumental data and the approximate location is a recent revision (A.E. Stevens, personal communication, 1983) of the location near Saint John published by Smith (1966). Thus the 1982 Miramichi mainshock, magnitude 5.7, is the largest earthquake in New Brunswick in historical times.

However, all or most of the province has been shaken by many other large eastern North American earthquakes, notably the Charlevoix earthquakes in 1663, 1860, 1870, 1925 and 1939, the Cape Ann, Massachusetts earthquake in 1755 and the Grand Banks earthquake in 1929. The last earthquake in eastern Canada with a magnitude similar to the Miramichi mainshock was the Cornwall-Massena earthquake of 1944. This event caused damage amounting to about $1,000,000 (1944 dollars) in each of the two cities on either side of the St. Lawrence River, but was felt only mildly in New Brunswick (see also Stevens, 1977).

The Miramichi Earthquake Sequence

The mainshock of magnitude 5.7 occurred at 08:53 AST on January 9 near 47.0N 66.6W. It was followed three and a half hours later by an aftershock of magnitude 5.1, and two and a half days later (January 11, 17:41 AST) by an aftershock (or second mainshock) of magnitude 5.4.

The intensity distribution of the main shock is shown in Figure 2. The inner isoseismal contour defines the general extent of Modified Mercalli V intensities, the outer, that of intensities III and IV. Intensity V is defined as "felt indoors by practically all, outdoors by many, many awakened, small or unstable objects overturned or moved, hanging objects, doors swing considerably". Intensity III is defined as "felt indoors by several, motion usually rapid vibration, duration estimated in some cases, vibration like that due to passing light truck, hanging objects may swing slightly, movements may be appreciable on upper levels of tall structures" (Wood and Neumann, 1931).

In the furnished, but unoccupied, cabins and cottages in the epicentral zone no evidence of displaced objects was found, although there was one unverified report that a stovepipe, lampshade and dishes had fallen to the floor. This apparently modest level of strong shaking in the immediate epicentral area might have occurred if the vertical component of ground motion was dominant and the horizontal

Figure 1 *Seismicity of New Brunswick and adjacent areas prior to the 1982 earthquake activity. Seismograph stations operated by the Earth Physics Branch. Major faults and granitic intrusions adapted from Williams (1978). Figure adapted from Wetmiller et al. (1984).*

forces were insufficient to topple small objects. There was no structural damage anywhere, although earthquake-induced hairline cracks were confirmed in a few buildings in Chatham, Newcastle, Bathurst and Perth-Andover up to about 100 km from the epicentre (Pernica and Maurenbrecher, 1982).

The outer contour in Figure 2 is the outer limit of the area over which the earthquake was generally perceptible at ground level (Intensity III). This area is well defined by the questionnaire surveys conducted by the Earth Physics Branch in Canada and the U.S. Geological Survey in the U.S. (Stevens and Cajka, 1984). The earthquake caused perceptible swaying in highrise buildings in Ottawa (750 km) and New York City (950 km), but it was not felt at ground level at these distances.

The magnitude 5.1 aftershock on January 9 was felt over most of New Brunswick with intensities of III to IV. The principal aftershock of magnitude 5.4 on January 11 was felt in all of New Brunswick, in parts of Nova Scotia, Prince Edward Island, the Gaspé and eastern Maine, with scattered reports from elsewhere in New England. The maximum intensities for this event might have reached V in some communities, but it is unlikely that intensity V was experienced over a significant area because most communities reported lower intensities than on January 9.

The numbers of aftershocks per hour during January, as detected at the nearest permanent seismograph at Edmundston (EBN in Fig. 1) are shown in Figure 3. Some additional aftershocks from mid-January to late-March were reported felt; then, on March 31 a magnitude 5.0 aftershock was felt over most of New Brunswick, the western half of Prince Edward Island and along the New Brunswick-Maine border. The largest recent aftershock was magnitude 4.1 in May, 1983. Events larger than magnitude 2.0 are still occurring weekly at the time of writing (March, 1984), more than two years after the main shock.

Aftershock Field Studies

On the afternoon of January 9 an Earth Physics Branch field party with portable seismographs flew to New Brunswick. By the afternoon of January 10 three instruments were in operation along Highway 108 about 25 km south of the epicentre, as close as the team could get in the severe winter conditions. Arrangements were made with the New Brunswick Department of Highways to plough open logging roads into the epicentral area that are normally passable only in summer. With much additional assistance from the New Brunswick Forest Service and Emergency Measures Organization, a total of 24 analogue and digital seismographs were eventually put into operation in the epicentral region. The Branch was assisted in this field program by teams and equipment from the Atlantic Geoscience Centre, the U.S. Geological Survey, three U.S. universities, two U.S. consulting companies and the U.S. Nuclear Regulatory Commission. Although there were many instrumental malfunctions due to the low temperatures, sufficient aftershock data were collected by January 22 that most of the field instruments were removed.

On January 28 a new outstation, as part of the Eastern Canadian Telemetered Network, was put into operation at Mt. McKendrick (KLN in Fig. 1) about 25 km southeast of the epicentral region, as close as the line-of-sight radio link would allow. This station has since provided a continuous monitor for the lower magnitude aftershock activity, although these aftershocks cannot be accurately placed within the active zone.

The rare opportunity to record strong seismic ground motion of engineering significance from a large aftershock led to a joint project with the U.S. Nuclear Regulatory Commission under which seven strong motion seismographs were installed in the epicentral region by February 6. These instruments were triggered by the March 31, magnitude 5.0 aftershock and a number of smaller events, including the May 1983, magnitude 4.1 aftershock. An analysis of the 1982 strong motion data has been presented by Weichert *et al.* (1982), and these data are receiving considerable attention from the earthquake engineering community because of their implications for the effects of future similar earthquakes on critical facilities in eastern North America.

The March 31 aftershock was of sufficient size to warrant another field deployment, and the Branch operated four seismographs in the epicentral region April 2-7. These data (as discussed below) played a significant part in the overall understanding of the earthquake sequence. On June 16 an earthquake of magnitude 4.7 occurred 30 km west of the January and March events. Because of the new location, a third field survey was conducted in the epicentral region of this event June 17-23. Although the focal depth and mechanism of the June 16 event were similar to those of the Miramichi sequence (Wetmiller *et al.*, 1984), there is no evidence to causally connect them. The June 16 earthquake is, therefore, assumed to be an independent event and is not discussed further here.

Searching for the Fault Break

The Miramichi epicentral zone lies on the axis of the Miramichi Anticlinorium that forms the central highlands of New Brunswick and that consists of a series of large granite plutons of Devonian age intruding Ordovician and older metasediments and granites. Faulting is known to affect some of the rock units of the anticlinorium, the Catamaran Fault in Figure 1 being a prominent example. It is a right-lateral, strike-slip fault that offsets the Early Carboniferous granite pluton south of the epicentral area (Fyffe, 1982a). However, no evidence for faulting younger than Paleozoic has yet been found on the Catamaran Fault, or for others like it, and it was not a causative factor in the 1982 earthquakes.

The earthquakes occurred within a massive Devonian granite pluton remarkably free of any surface evidence of previous deformation (see Fig. 4). A subsequent gravity survey (Burke and Chandra, 1983) has shown that the pre-Devonian deformed granites and metasediments represent only a thin cover (0-1 km) to the main

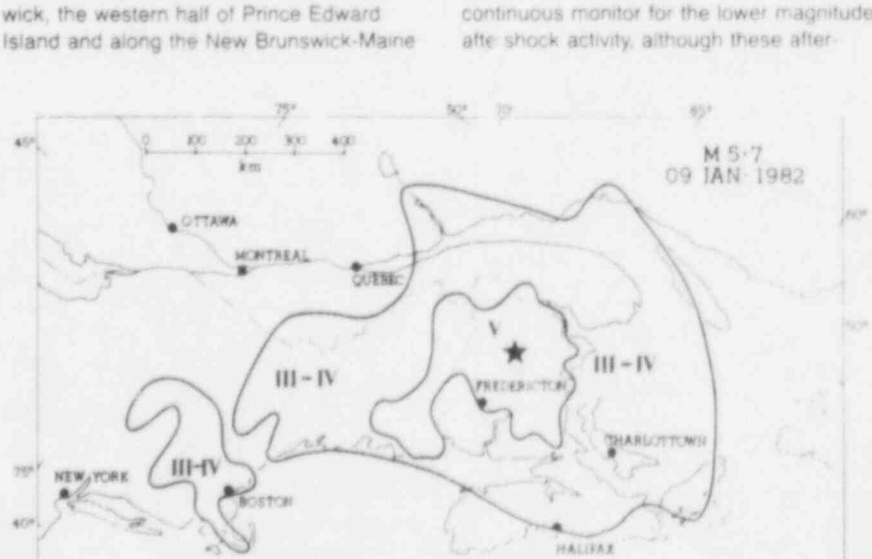

Figure 2 *Isoseismal contours of January 9 mainshock showing extent of Modified Mercalli intensity V and III. Adapted from Stevens and Cajka (1984).*

granite pluton and that the granite pluton is probably 8 km thick. Hence, most of the aftershocks probably occurred entirely within the granite pluton. The gravity data suggest that the dioritic bodies within the pluton are more extensive than as mapped on Figure 4, but that they are probably thin (0.5 – 1 km) tabular bodies.

At the request of the Earth Physics Branch, the Canada Centre for Remote Sensing scheduled a flight over the epicentral area on January 13. However, aircraft problems and bad weather delayed the flight until January 19, by which time 0.5 m of fresh snow had fallen, effectively masking any subtle earthquake effects that might have been visible earlier. A careful search of stereoscopic air photos of the epicentral region revealed no earthquake-related features. A lineament map which shows a dominant trend of linears in a WNW direction was prepared from the photos (Adams, 1982). Many of these linears are now thought to be concealed shear zones like the two WNW trending shears mapped by Fyffe (1982b) and shown in Figure 4.

In May, 1982, after the snow had melted, a geological field survey was conducted in the epicentral area. Although the large size, shallow depth and thrust mechanism of the mainshock suggested that a primary surface rupture might have occurred, no significant fault break was found. Assuming a rupture area of 20-25 km^2, as indicated by the aftershock distribution, the average slip on the fault was 25-35 cm (Wetmiller *et al.*, 1984). Vertical thrust displacement as small as 100 mm across any of the dirt roads in the area would not have been missed; but off the roads much larger displacements could have gone undetected. Although a 100 mm or larger displacement would certainly have been seen had it occurred in one place, it is possible that the bedrock displacement at shallow depths occurred as a number of individual displacements on parallel splay faults that cumulated to the total slip.

In the southeast corner of the aftershock zone glacially-smoothed bedrock was discovered to be displaced by very recent small-scale thrusting on a pre-existing joint (Fig. 5). The joint belongs to a minor orthogonal set that trends 000 and 090 and that may have been produced by a more recent (post-Triassic) stress field than the one responsible for the majority of the jointing (Lajtai and Stringer, 1981). The thrust joint could be traced 3 m across the outcrop and involved 25 mm of thrust displacement, west side up, along a joint trending N5E that dipped at 40° to the west. Additional field work in the area of the thrust joint is described below.

Aftershock Distribution and Speculative Fault Planes

The epicentral distribution of the January and April activity (Fig. 4) is defined by those aftershocks judged sufficiently well located. Considering the uncertainties in the crustal velocity model and the distribution of temporary seismograph stations, the absolute uncertainties in the epicentral locations are not likely to be smaller than ±1 km. Uncertainties in estimates of focal depth are not likely to be smaller than ±2 km. The January activity was diffuse, but confined principally to a volume 6 km on a side, with the deepest events at about 7 km. In cross section the least scatter is produced when the hypocentres are projected onto an east-west plane (Fig. 6a). Most of the January activity was concentrated in the southwest portion of the active volume. The April epicentres are concentrated in the northeast portion of the January activity and the depths are generally shallower. In Figure 6a the distribution of after-shocks suggests a north trending conjugate "V" pattern.

P-wave first-motion and surface-wave analyses of the magnitude 5.7 mainshock using data from Canadian seismograph stations suggest thrust faulting on a north-striking plane dipping about 50° (to either the east or west), the causative stress being east-west compression (Wetmiller *et al.*, 1984).

If the aftershocks on Figure 6 are divided into four groups, shallow and deep, west and east, the composite P-nodal solutions (i.e., solutions using the combined results from a group of aftershocks) for each group suggest steeper dips at shallower depths. The western groups of January events show dips of about 47° at depth and 63° near the surface; the eastern groups of April events show dips of about 42° at depth and 78° near the surface. Thus, the dip of the mainshock plane seems to be representative of the rupture at depth. The aftershock analysis further suggests that both east- and west-dipping rupture planes steepen toward the surface. From an analysis of broadband displacement and velocity records of P-waves at teleseismic distances, Choy *et al.* (1983) suggested that the mainshock ruptured up dip on a west-dipping plane.

Figure 3 shows that the magnitude 5.4 event on January 11 had the most intense aftershock sequence. Therefore, most of the January aftershocks in Figure 6a are associated with this earthquake, and their locations suggest that the earthquake ruptured the east-dipping plane. At the present time there is no other independent evidence to specifically associate the magnitude 5.4 with this plane.

The following hypothesis has emerged (Fig. 6b): The January 9 mainshock occurred as a thrust with rupture up dip on a west-dipping plane. The exact location

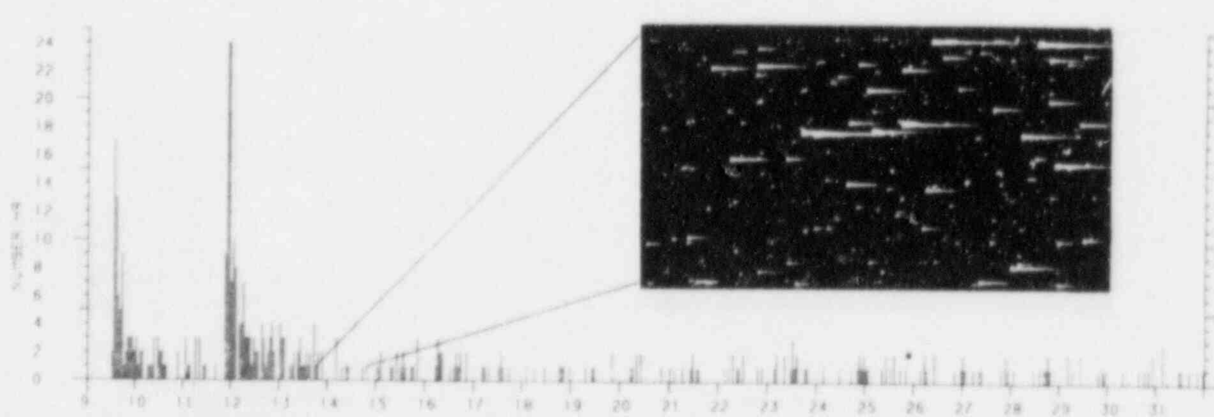

Figure 3 *Number of Miramichi earthquakes per hour detected at EBN seismograph station (Fig. 1). Inset shows field recording of 237 aftershocks in a 25-hour period, January 13-14.*

of the magnitude 5.1 aftershock three and a half hours later is not known independently, but on sparse evidence given by Choy *et al.* (1983) it has been assigned to the lower northern portion of this same plane. Then, on January 11 the magnitude 5.4 event ruptured (probably up dip) a conjugate east-dipping plane and was followed by an intense sequence of smaller aftershocks. Finally, the March 31, magnitude 5.0 aftershock occurred as a repeat rupture in the upper northern portion of the west-dipping plane. In this description each of the two principal ruptures is assumed to be on a single plane, with the additional evidence, described above, that these planes steepen toward the surface. Another possibility is that the shallower aftershocks are associated with steeply dipping splay faults coming off a more shallowly dipping principal fault at depth. Three speculative alternatives are illustrated for the west-dipping plane in the lower portion of Figure 6. These alternatives illustrate the uncertainty as to where the principal rupture planes may lie relative to the aftershocks. In (c) it is assumed that the up-thrown wedge has become unstressed and the aftershocks are occurring beneath the main rupture planes; in (d) the aftershocks (with their recognized location uncertainties) are clustering about the main rupture planes; in (e) most of the aftershocks are in the up-thrown wedge. Which of these possibilities, or some other, is correct cannot be determined from available information.

Examination of the literature gives few examples of the accurate location of thrust fault planes relative to their aftershocks. Aftershocks associated with the southwestern half of the rupture zone of the 1980 El Asnam thrust earthquake are, clearly, mainly in the footwall, with relatively little activity on the fault plane (Figs. 7-9 in Ouyed *et al.*, 1983). However, in the northeastern part the aftershocks appear to lie mainly in the hanging wall (Fig. 10, Ouyed *et al.*, 1983), behaviour thought anomalous by Ouyed *et al.* Jackson *et al.* (1982) note that aftershocks on shallow dip-slip faults often concentrate in the hanging-wall block and attribute this to internal deformation resulting from either curvature of the fault plane or from non-uniform slip on it. One possible example is the induced seismicity at Nurek reservoir, U.S.S.R. (Leith *et al.*, 1981), which is almost entirely confined to the hanging-wall block above a major thrust plane that steepens towards the surface.

We suggest that the number, location and nature of aftershocks near a shallow thrust fault is probably controlled by the geometry of the thrust plane. A thrust plane that becomes less steep as it approaches the surface will apply less compressive stress to the hanging-wall block, so fewer aftershocks will occur there relative to the footwall which is still stressed. Very shallow aftershocks that occur above a gently-dipping thrust might exhibit secondary, normal focal mechanisms. At El Asnam normal faulting occurred on the ground surface of the hanging-wall block, although this localized extension in a compressional environment could be due to uneven fault slippage (more fault slip at depth; King and Brewer, 1983) or termination of the rupture at a bend, rather than to a change in dip of the thrust fault.

In contrast, a fault plane that steepens near the surface – as we believe do the Miramichi fault planes – will apply additional compressional stress to the hanging-wall block, which will thus become the locus of most of the aftershocks. These will still occur in a compressional environment, and so will have thrust mechanisms similar to those of the main shock. A concentration of aftershocks above the main rupture plane could also result from slip increasing towards the surface on a planar fault, although fault slip that increased towards the surface would make the absence of a surface rupture even more puzzling. For this reason, and because the Miramichi composite fault plane solutions show the steepening of the fault planes directly, we consider that uneven fault slippage provides a poor explanation for the Miramichi observations.

East-West Horizontal Stress

In September, 1983, as a cooperative project among the Atomic Energy Control Board, the Geological Survey of Canada and the New Brunswick Department of Natural Resources, the bedrock in the region of the thrust joint (Fig. 5) was cleaned off over an area 100 by 30 m (Fyffe, 1983). The observed thrust displacement of 25 mm was found to die out to zero, 1 m to the north of the original outcrop. To the south of the original outcrop the bedrock surface drops 150 mm across an east-west vertical joint, and on the lower block the thrusting decreases to 5 mm and then dies out completely. It is clear from field observations that the thrusting does not continue to any significant depth and probably dies out along sub-horizontal sheeting fractures. Although the orientation and nature of the thrusting are very similar to the deduced focal mechanisms, we interpret the thrust joint to represent the relief of surficial stresses that were released by the earthquake shaking, rather than a primary rupture.

In addition to the thrust joint, a small stress-relief buckle occurred in the bedrock overnight between two examinations of the outcrop (Fig. 7). A slab of diorite about 3 m long, 1 m wide and 50-100 mm thick buckled up 55 mm from the underlying bedrock along a sub-horizontal fracture. The separation has since increased to 80 mm. The slab was in contact with the intact bedrock at either end, but in the centre had cracked along a general trend of 010, i.e., more or less parallel to the thrust joint and to the strike of the fault planes determined from the composite focal mechanisms. A further incipient buckle – a diorite slab separated vertically from the underlying rock by a few mm on a sub-horizontal fracture – was also seen. As less than 1 m of overburden had been removed, the confining pressure that previously prevented the buckle was not great, suggesting that the rock was already close

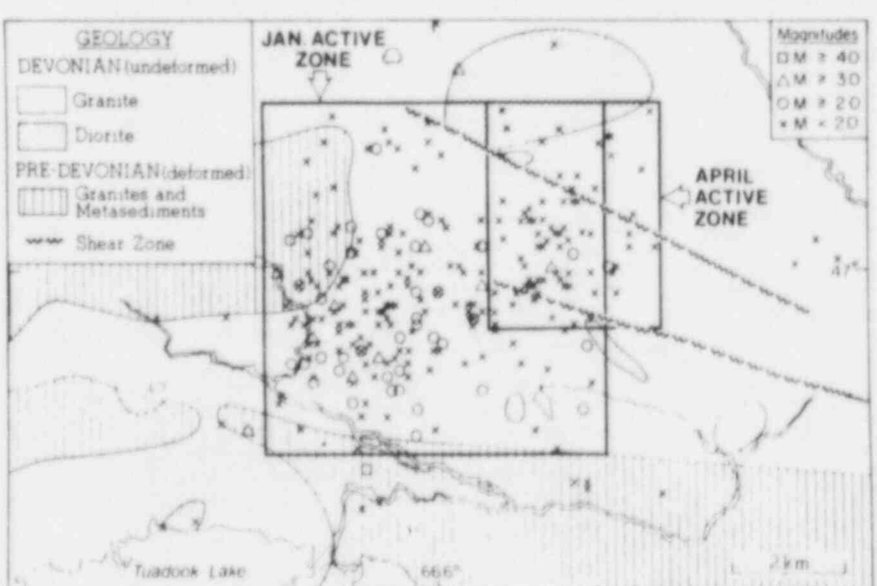

Figure 4 *Epicentres of January and April aftershocks superimposed on the geology of the epicentral region, from Fyffe (1982b). After Wetmiller et al. (1984).*

to failure. The size of the buckle provides a crude estimate (by calculating the probable strain change and estimating a Young's modulus) of 5 MPa for the horizontal surface stress relieved.

The stress-relief phenomena on the cleaned-off outcrop (buckle and thrust joint) indicate both high horizontal stresses and east-west compression. Further, the eight composite focal mechanisms for the Miramichi aftershocks and the independent Trousers Lake earthquake all have nearly horizontal east-west directed P-axes (Wetmiller *et al.*, 1984) and hence are consistent with E-W compression. Some oil well breakout data from the Gaspé and the Maritime Provinces (Cox, 1983) indicate regional E-W to NE-SW compression, although some other measurements close to the Miramichi – in southern New Brunswick and Prince Edward Island – have varied stress directions within the same well. Direct measurements of stress have been made by Golder Associates for Brunswick Mining and Smelting in their Bathurst Mine, 75 km north of the Miramichi epicentral area (C. Pagel, personal communication, 1983). At 1 km depth the ESE-WNW horizontal stress is about 55 MPa, the NNE-SSW stress is 33 MPa, and the vertical is 23 MPa.

The general consistency of regional stress orientations and their specific agreement with the local stresses confirm that New Brunswick is subject to horizontal compression with the maximum horizontal component in an E-W direction. The challenge in the next few years will be to determine the present state of stress in the epicentral area, to discover how the earthquakes modified the initial stress field and to understand why the stresses were concentrated and released within the pluton.

Implications for Seismic Risk Estimation

The Earth Physics Branch has recently prepared new seismic zoning maps for the 1985 edition of the National Building Code (Basham *et al.*, 1982). This work was essentially complete prior to the Miramichi earthquakes. The method used in deriving these maps requires a model of earthquake source zones for all seismically active regions of the country. New Brunswick is part of a Northern Appalachians source zone in which a random distribution of future earthquakes is assumed throughout the southern three quarters of the province and the northern New England states. The assumption of random occurrence throughout an arbitrarily defined zone was required because it was not possible to identify regional geological features that controlled the distribution of seismicity (as noted above with respect to Fig. 1).

The risk calculations also require esti-

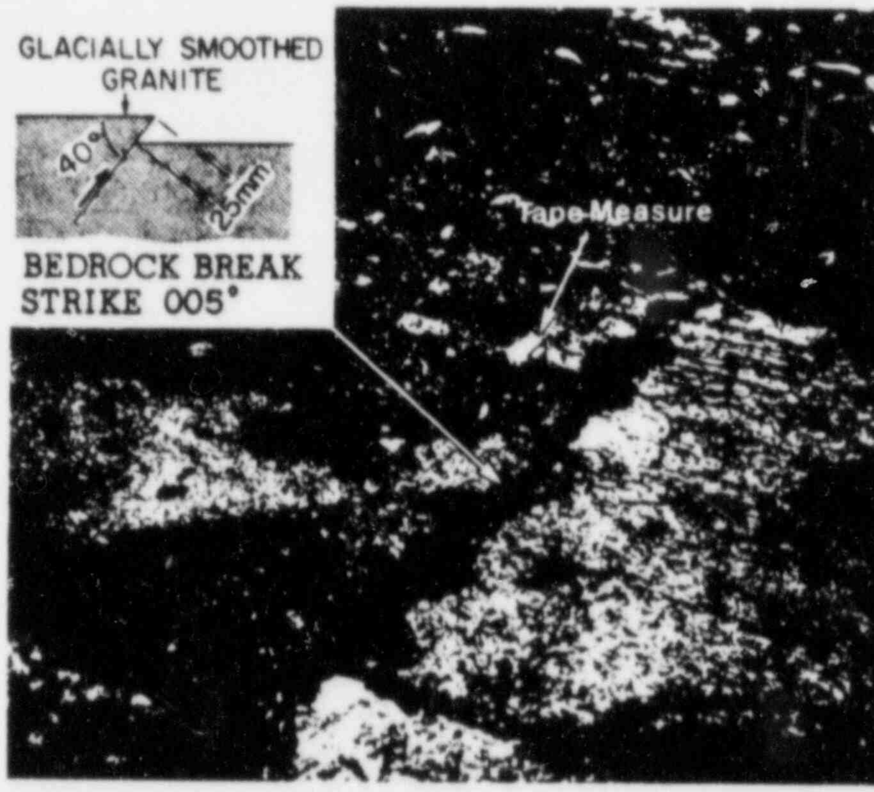

Figure 5 *The observed ground break with an east-west cross section showing the relative displacment. The location of the break in an east-west section of aftershock hypocentres in shown in Figure 6a. After Wetmiller et al. (1984).*

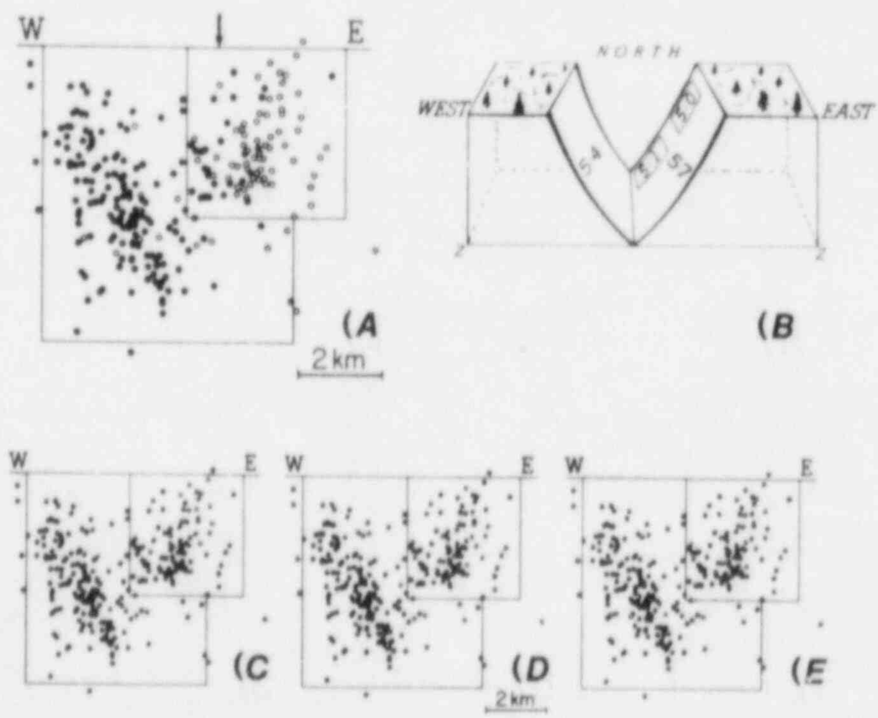

Figure 6 *(a) East-west cross section of January (solid circles) and April (open circles) aftershock hypocentres. (b) Possible Miramichi rupture planes. View is from the south looking north, and number on each plane identifies the magnitude of the earthquakes. (c,d,e) Three alternative sets of speculative rupture planes superimposed on aftershock distribution from (a). The relative location of the bedrock crack (Fig. 5) is shown by the arrow. Horizontal and vertical scales are equal.*

mates of earthquake rates as a function of magnitude (determined from historical and recent seismicity), and an upper bound magnitude. For the Northern Appalachians source zone, the upper bound magnitude was set as 6.0, an arbitrary value selected as being somewhat larger than the then known largest historical event. Lack of neotectonic constraints (e.g., dimensions of potentially active faults) prevented determination of the relevant value. The Miramichi mainshock came close to, but did not exceed, this upper bound.

A recalculation of the seismic ground motion with the Miramichi earthquakes added to the Northern Appalachian model has shown that the zoning maps would not change significantly. The computed ground motion would increase by about 5 percent of its value, which is well within the uncertainty in the original calculations.

The current understanding of the focal parameters and inferred faulting of the Miramichi earthquakes (as summarized above) is much better than for any equivalent magnitude earthquakes anywhere in eastern North America. However, in spite of this, we are not yet much closer than before to having a general understanding of the types of geological features or structures on which similar earthquakes will occur in the future, i.e., the random earthquake model still provides our best estimates. Further work in Miramichi may provide additional clues.

Work in Progress

Three field projects in addition to the bedrock cleanoff project described above were conducted in the Miramichi epicentral zone in the summer of 1983. A number of sites were occupied by analogue and digital seismographs to record continuing aftershocks, and two calibration explosions were detonated in shallow holes to determine more accurate local crustal velocities. The aftershock survey was designed to determine accurate hypocentres of continuing activity in the shallow portion of the eastern aftershock cluster (Fig. 6). The data are now being analyzed and it is hoped that the results will more clearly define the near surface faults on which the aftershocks are occurring and, thereby, provide better target areas for a further search for the surface expression of the faults.

A magnetotelluric (MT) survey was conducted using both tensor MT and scalar audiomagnetotelluric (AMT) techniques. Tensor MT soundings were made at eleven locations inside and on the edges of the epicentral region to establish the conductivity structure throughout the crust. Scalar AMT measurements were made at seventy-six locations along an E-W profile in the east-central portion of the zone. These measurements were designed to look for a conductivity signature of one or more postulated shallow rupture planes. Both sets of data are now being analyzed and any positive results will also aid in determining the nature and location of the rupture planes.

A NW-SE trending electromagnetic anomaly was located near Indian Lake, in the SE corner of the epicentral zone, by the New Brunswick Department of Natural Resources (J. Chandra, personal communication, 1984). Two trenches were cut across the anomaly and revealed an apparent gouge, or mylonite zone, separating unweathered and strongly weathered granites of different lithology, the lithology difference probably being sufficient to account for the weathering difference. There was no firm evidence for young displacement on the gouge zone, although gouge material appeared to have been dragged up into the till along the direction of ice movement.

Future Work

Our investigations of the epicentral area are by no means concluded. In 1984 a multi-agency project led by Ontario Hydro intends to make direct measurements of horizontal stresses at four or five sites within and outside the epicentral area. The measurements will be made by overcoring in 15 m-deep holes, and should provide valuable data about regional and local post-earthquake stresses. Also in 1984, the Earth Physics Branch will lead a second multi-agency project to expose bedrock along a narrow strip across the expected surface outcrop of the west-dipping rupture plane. The search for a surface rupture – which if found will be the first to be associated with a historical earthquake in northeastern North America – is important: comparisons will be made with our seismic estimates of rupture displacements at depth, and it will enable us to test models that seek to explain the lack of such ground breakage during previous earthquakes in eastern North America.

Looking still further into the future, we hope that it will be possible to fund a high resolution seismic reflection survey to attempt to map in detail the fault planes at depth and to determine the degree to which the faulting has altered the integrity of the rock mass. If such mapping is successful, it may be possible to "see" the faults directly and improve our understanding of the events and processes during this remarkable earthquake sequence.

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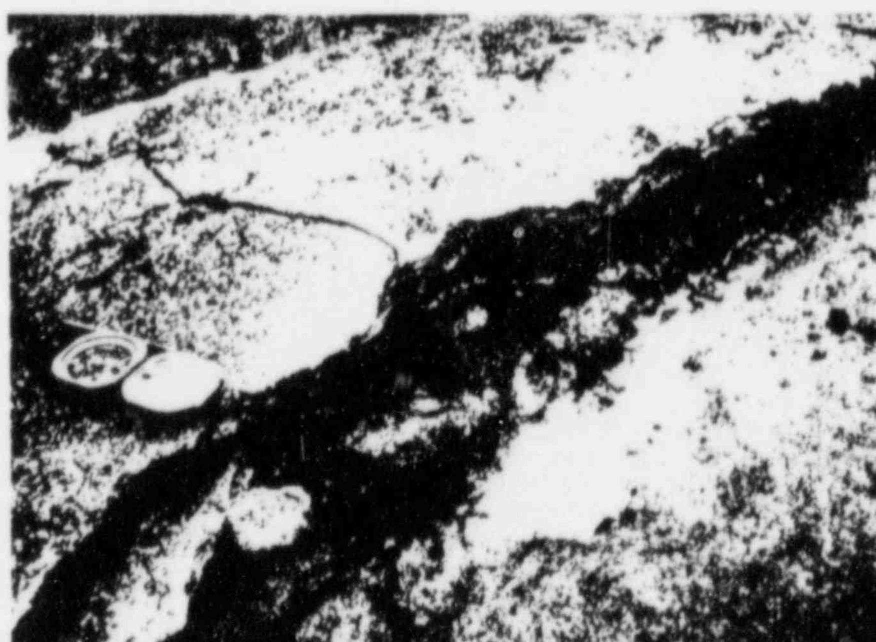

Figure 7 *View of pop-up induced by removing till overburden. Note axial crack, gap under buckled slab, and dirt piled up against former position of slab. Compass provides scale and points north.*

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12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)

This Final Report provides a comprehensive summary of the activities of the Earth Physics Branch (EPB) in eastern Canada, particularly with respect to the Eastern Canadian Telemetered Network (ECTN). The report describes the seismographic system developed by EPB to monitor the regional seismicity. There are detailed descriptions of the logic used to select the various physical components of the system, the hardware and software that constitute the recording system, and the data flow from detection to archive.

In addition to the engineering details, there is a discussion of the scientific results from the analysis of the regional seismicity during the reporting period. Particular emphasis has been placed on the Miramichi, New Brunswick earthquakes of January 1982.

14. DOCUMENT ANALYSIS – a. KEYWORDS/DESCRIPTORS

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Canada Seismograph

b. IDENTIFIERS/OPEN ENDED TERMS

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